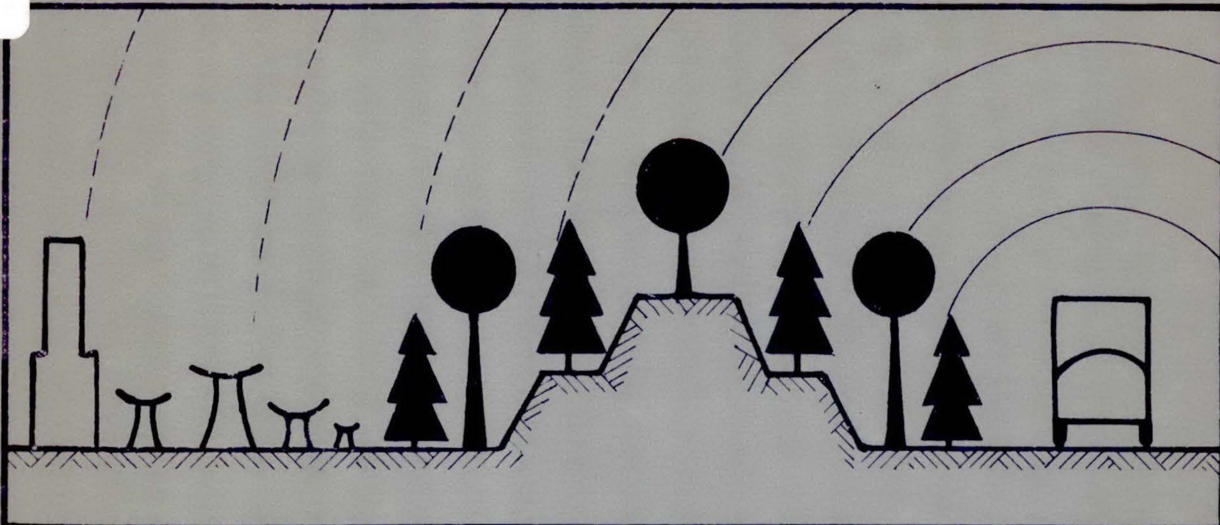
FORESTED LAND-FORMS



FOR NOISE CONTROL

FINAL REPORT
OF A STUDY
CONDUCTED BY THE
UNIVERSITY OF NEBRASKA
AND THE
U.S. FOREST SERVICE

SUBMITTED TO:
FOREST SERVICE
U.S. DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

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FORESTED LAND-FORMS
FOR NOISE CONTROL

A Report of a Study Conducted by

The University of Nebraska and the U.S. Forest Service

Principal Investigator: David I. Cook - Department of Engineering Mechanics

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November 1973

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FOREWORD

This study was an extension of a previous study "Trees and Shrubs for Noise Abatement" (11), and was conducted jointly by the University of Nebraska and the Forest Service, U. S. Department of Agriculture. The objective was to determine means for controlling intrusive noise by combining trees and shrubs with land-forms or other solid barriers. The solid barriers would provide some immediate relief, and the plant materials would increase the protection as they matured.

Personnel conducting the research were Professor David I. Cook, Department of Engineering Mechanics, principal investigator; Dr. David F. Van Haverbeke, Research Forester, Rocky Mountain Forest and Range Experiment Station, and Mr. Thomas J. Von Aschwege, student of Civil Engineering, University of Nebraska. Statistical analysis of the data was under the direction of Jacob L. Kovner, Biometrician, Rocky Mountain Forest and Range Experiment Station. Credit is due Dr. Carl Berntsen, Assistant Director of the Rocky Mountain Station for encouragement in extending the preceding study to this one, and to Ralph A. Read, Project Leader, for providing support services and reviewing the manuscript.

The Rocky Mountain Forest and Range Experiment Station is head-quartered in Fort Collins in cooperation with Colorado State University. Dr. Van Haverbeke is stationed in Lincoln in cooperation with the University of Nebraska.

SUMMARY

Combinations of trees, shrubs, and solid barriers are effective means for shielding sensitive areas from intrusive noise. Reductions of sound levels in the order of 10 to 15 decibels (less than half as loud) are common for 12-foot-high land-forms combined with wide belts of tall trees, and greater reductions have been observed in many instances.

Trees and solid barriers appear to be complementary in reducing noise levels when they are used in combination. Either trees or solid barriers may be used separately, but the combination tends to provide more uniform control for a greater distance than does either one separately.

Relative placement of the barrier between the noise source and the protected area is of great importance, as is the overall sound propagation distance. Generally, a barrier placed close to a noise source is more effective than one placed midway between source and receiver.

Screening is effective only when the noise source is hidden from view at the protected area, and the effectiveness increases as the height of the screen is increased. Optimum heights are suggested for several applications.

A supplementary study indicated a combination of concrete block walls with relatively young evergreens would be effective in reducing noise within a residential area.

INTRODUCTION

The effectiveness of trees and shrubs in reducing noise was demonstrated in the previous study, reported in University of Nebraska Research Bulletin 246, "Trees and Shrubs for Noise Abatement." (11). However, wide, dense belts of tall trees were found to be necessary for rural applications, and several years would be required to develop a massive tree structure of the size required. Often the urgency of a situation does not permit such a development, and other means have to be sought. In such a situation, trees and shrubs might be combined with solid barriers with increasing benefit to provide some immediate relief from intrusive noise, with increasing benefit as the plant materials mature.

Both natural and adaptable test sites were studied. A solid land-form of varying height was constructed at one site, and concrete block walls of different heights were constructed at another. Three of the sites had existing natural land-form barriers.

Tape-recorded truck noise was used as a noise source in most of the experiments, although actual noise of passing vehicles was also used in some instances. A power lawnmower provided the noise source for a suburban test site. For all tests the sound was projected toward a barrier, and the sound level was measured at varying distances behind the barrier. The procedure was repeated at nearby locations devoid of barriers, but otherwise identical, to evaluate barrier effectiveness.

As in the preceding study the dBA scale of sound level measurement, which approximates human response to the loudness of broad-band noises, was used for most of the measurements and in reporting the results.

Four of the five sites selected were noticeably different in

character, and each site is discussed separately. Results are presented as curves showing the sound level at varying distances from the noise source, and the reduction in sound level (attenuation) due to the presence of the barrier.

Equations were developed to predict the sound level at various distances from the noise source for the different heights and types of barriers studied.

A supplementary study of short-distance noise propagation, as might be found in suburban areas, was less extensive than were the other types, and future studies of this type seem desirable.

Observations and conclusions of the report describe the interrelationship of trees and solid barriers when used as noise control devices, and suggest reasons for the observed phenomena. Specific recommendations are made for using combinations of trees and land-forms to reduce intrusive noise.

The reader is encouraged to refer to the earlier report for background material derived from tests of tree-belts alone. Lists of references and plant materials suitable for noise screening have also been included from the earlier report, as have detailed descriptions of items of equipment used in both studies.

Review of Literature

Several studies of the acoustical properties of plant materials and several studies of the acoustical properties of solid barriers have been made, but very few studies of combinations of the two appear in the literature.

Several well-known studies, cited in Appendix D, include "Jungle Acoustics" (15); "Sound Propagation in Homogeneous Deciduous and

Evergreen Woods" (14); "Propagation of Sound over Ground" (38) and "Effect of Highway Landscape Development on Nearby Property" (7).

More recent studies, also cited in Appendix D, include "Noise Control in Britain and other European Countries" (12). Studies in Great Britain have indicated that vegetation planted on sloping sides of highway cuts can help absorb sound, and that a 10-foot high retaining wall on a sub-surface motorway reduces the noise level by 12 dBA (less than half as loud) near the road. Another British study "Traffic Noise" (35) states that if sufficient land is available, the most effective way of reducing the spread of motorway noise is by the use of enbankments covered with grass or planted with bushes. The German publication "GARTEN UND LANDSCHAFT" (16) has published an article, based on a workshop study in November 1971 entitled Street Traffic Noise and Landscape Planning. The article describes the use of plantings and embankments to reduce street noise. Expected results are based on model studies, and values are given for tree plantings alone as well as for tree-covered embankments. "Civil Engineering" (2) describes a proposed expressway through a section of Baltimore, Maryland which would use walls and embankments to protect surrounding areas from traffic noise. Wylie Laboratories have recently completed a theoretical study for the armed services, which predicts the reduction of sound level over various types of terrain and at different elevations (31). Model studies have been proposed in an article in "SCIENCE" (28) which might be used to predict noise levels within an urban area, where reflecting surfaces are frequent, and where, because of natural variations, precise measurements are difficult to obtain in the actual case.

CHAPTER I FACILITIES, EQUIPMENT AND PROCEDURE

DESCRIPTION OF TEST SITES

Three natural sites and two modified sites were used for the research. Site 1, a modified site, was located adjacent to U. S. 34 highway near Hastings, Nebraska on Forest Service property. A specially constructed land-form, and a 100-foot-wide tree belt provided the necessary variables. Sites 2 and 3, natural sites, were located adjacent to U. S. 34 near Milford, Nebraska. A highway cut topped by a wide belt of trees, and having a clear field behind the belt provided the necessary variables. Site 4, a natural site, was located at a rest area on Interstate 80 near Gretna, Nebraska. An existing hill between the highway and adjacent parking area served as a variable height land-form for study. Passing trucks served as the noise source. Site 5, a modified site, was located on the Horning State Farm of the University of Nebraska Department of Horticulture and Forestry, near Plattsmouth, Nebraska. A four-row belt of 8-year old mixed conifers was used in combination with a concrete block wall of varying height to serve as a noise screen.

More complete descriptions of the sites appear in Chapter III - Results of Experiments.

NOISE SOURCES RECEIVERS AND EQUIPMENT

Three types of noise were selected for the study. Tape recorded truck noise, as used in the previous research (11), was used extensively at sites 1, 2, and 3. Actual sound of passing trucks was also used at site 1, to a limited extent. Actual sound of I-80 highway traffic (mainly from trucks) was used at site 4, and actual sound of a power

lawnmower was used at site 5.

A general Radio sound level meter type 1551C, a Bruel and Kjaer sound level meter type 2205, a General Radio Data Recorder type 1525A, and a General Radio Octave Band Analyzer type 1558BP were used separately in some tests and concurrently in others to measure and record the sound. Instruments were calibrated with a General Radio sound level calibrator, type 1562-A. A portable electric generator supplied power for the sound system and data recorder.

Meterological equipment consisted of thermometers, hygrometer, and a wind speed and direction indicator. A double wind screen was used to cover the microphone during periods of moderate wind.

EXPERIMENTAL PROCEDURE

The overall procedure was based on a comparison of sound levels with and without the presence of a tree and land-form acoustical screen. Special adaptations of the procedure were made at each site as required. At Site 1 prerecorded truck noise was first projected toward the specially constructed acoustical screen, which consisted of a land-form placed half-within and half-without a belt of trees, and the attenuated (reduced) sound was measured behind the screen at various distances from the edge of the tree belt. The same prerecorded sound was then projected toward the portion of the land-form which was not covered by trees, and the reduced sound was again measured. Finally, we projected the sound over a level, unobstructed surface -- referred to as a control surface -- to determine how much of the attenuation was attributable to the tree-covered land-form and to the bare land-form.

A noise source level of 91 dBA measured 50 feet from the horn was adopted as a reference for most of the tests. Projections were made at

about 5 feet above the ground surface, and microphone heights of approximately 5.5 feet were used. All sound projections were at right angles to the belt, representing the worst condition of intrusive noise entering a sensitive area.

Actual sound of passing trucks also served as a noise source at Site 1; then the procedure was modified to allow for the variation of sound level from truck to truck. Three sound level meters were used to measure the noise of a single truck as it passed by the test site. One measurement was made behind the tree-covered land-form, a second behind the bare land-form, and a third in the unobstructed (control) area. For this type of test only the reductions of sound level (attenuations) have meaning, since the source level of individual vehicles varies. Additional measurements were made at several distances from the noise source to complete the test series.

The procedure for experiments at sites 2 and 3 -- the tree-topped highway cuts -- was similar to site 1 procedure, except that tape-recorded sound was used exclusively at these sites. The procedure at site 4 -- the I-80 rest area -- consisted of taking three sound level readings in close succession of the noise generated by a truck as it passed by the hill. One reading was taken opposite the entrance ramp where the hill was of negligible height, a second was taken behind the hill, and a third was taken opposite the exit ramp, where the hill was also very low. Readings were repeated at various distances from the highway to obtain a "noise profile" of the hill and area immediately behind it. Since individual noise levels of the trucks vary, the attenuations were used as a basis for the comparison, to show how much the sound was reduced by the grass-covered hill.

The procedure for experiments at site 5, the Horning State Farm, differed from that of the other sites in several ways. A power lawnmower was used as a noise source. A concrete block wall was constructed within a belt of trees, and a similar wall was constructed in an open (control) area. The height of both walls was varied by adding and removing blocks. Shorter distances were used than in the previous tests, as it was desired to simulate suburban conditions. Distances from noise source to wall and receiver to wall were varied progressively in an attempt to find the optimum wall placement between a noise source and an area to be protected.

All control tests were designed to duplicate the physical conditions of the regular tests to improve the accuracy of the results. Control tests were made immediately before or after regular tests to minimize the effect of atmospheric changes of wind and gradient. Nearly identical terrain was used for control tests and regular tests, to minimize the effect of surface variation. Instruments were calibrated frequently, and emission levels of tape-recorded sound were checked before and after each test run.

Upwards of 10,000 individual readings were taken at the five test sites during the series of experiments. A minimum of four and as many as 12 readings were taken at each microphone position, depending on the amount of variation.

Most experimental results were reduced to graphical form for ease of interpretation. Average curves of sound level versus distance and attenuation versus distance were drawn. Experimental data were analyzed statistically to obtain prediction equations for design purposes.

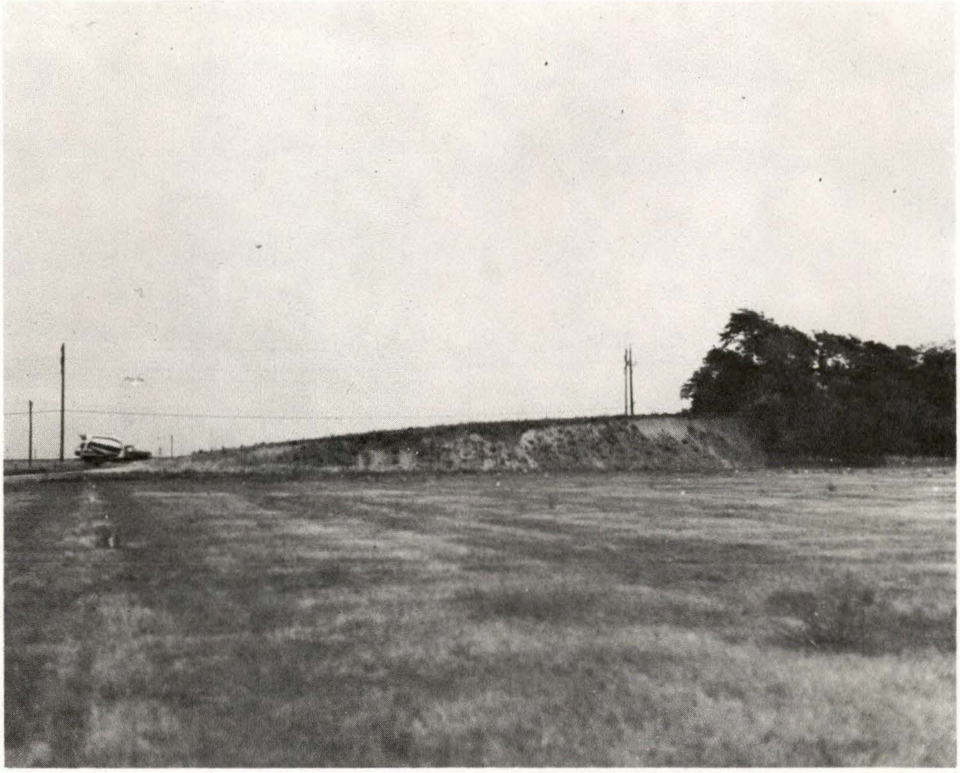
CHAPTER II RESULTS OF EXPERIMENTS

SITE 1 - HASTINGS LAND-FORM

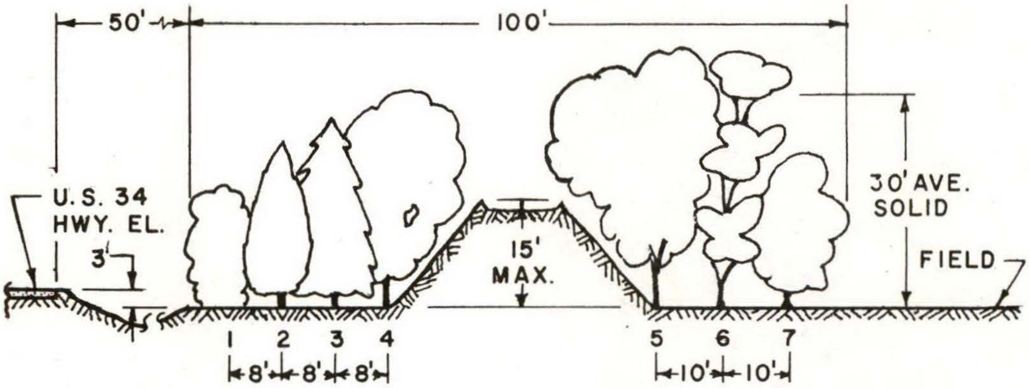
This site, located on Forest Service property on the south side of U. S. 34 highway 3 miles east of Hastings, Nebraska, was the principal test site for the study. An existing 11-row shelterbelt of mixed conifer and deciduous trees was modified by removing the center four rows of trees, and constructing a variable height land-form in their place. The land-form was extended an equal distance beyond the end of the belt so that a symmetrical configuration outside and within the belt resulted (Figs. 1 & 2).

Tape-recorded sound was projected toward this acoustical screen, and sound levels were measured behind the screen at a series of positions illustrated in Fig. 2. It may be noted that the noise source was located approximately fifty feet in front of the belt edge and the receiving microphone was placed at distances varying from zero to 300 feet from the rear edge of the belt, giving overall transmission distances from 150 to 450 feet.

The noise reduction characteristics derived from the measurements are illustrated in Figs. 3 to 7. The sound level at any distance from the noise source may be read directly from the upper curves, and the "relative attenuation" (sound level reduction) may be read from the lower curves. These curves are termed "relative attenuation" curves because they show the sound level measured behind the tree-land-form barrier relative to the sound level measured over a comparable flat surface. Thus the reduction is attributable exclusively to the presence of the barrier. A theoretical curve for a point source sound projection



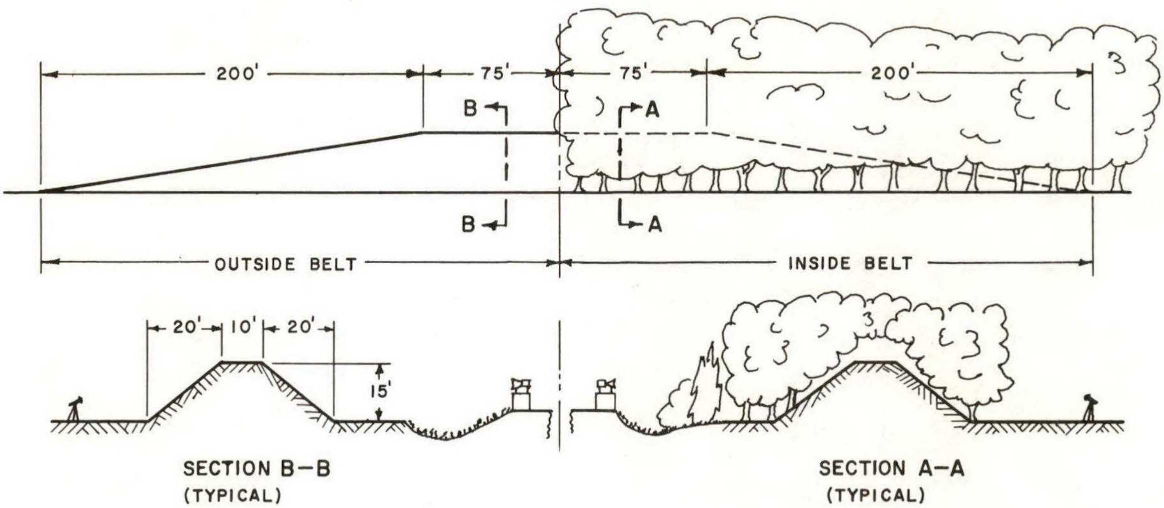
SITE I
HASTINGS BELT AND LAND-FORM



ROW NO.	NAME OF TREE	SPACING IN ROW
1	LILAC	3'
2	EASTERN REDCEDAR	4'
3	PONDEROSA PINE	5'
4	GREEN ASH	5'
5	SIBERIAN ELM	5'
6	HONEY LOCUST	5'
7	MULBERRY	4'

Fig. 1

HASTINGS LAND-FORM



FIELD OF MEASUREMENTS

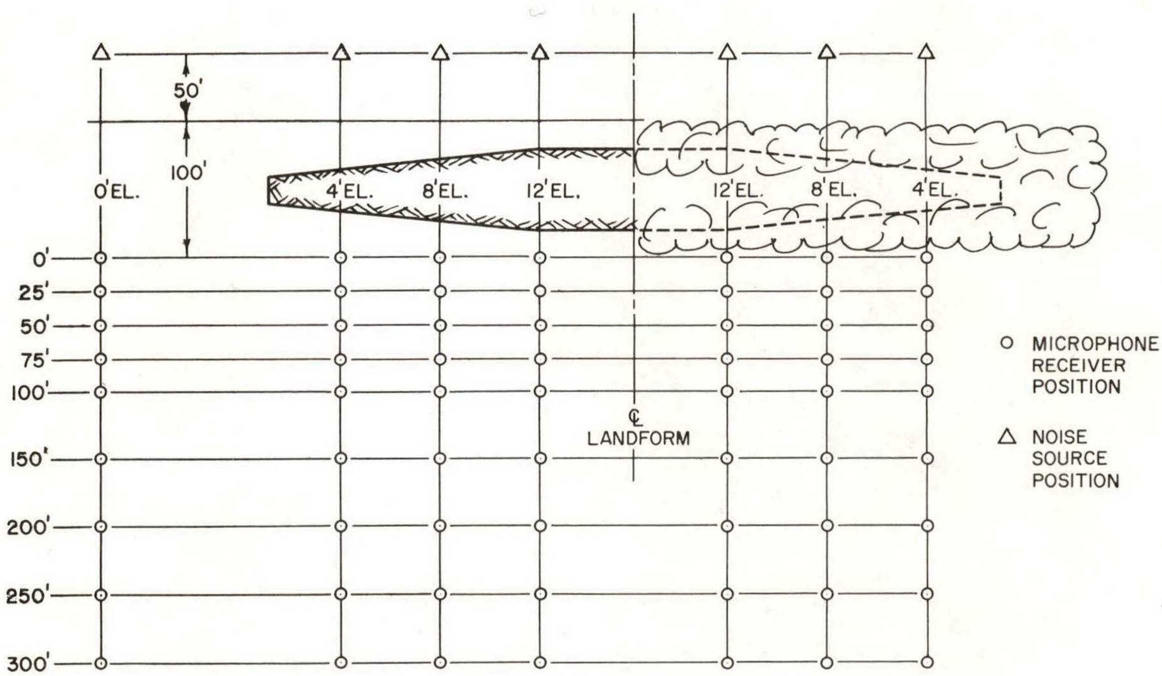


Fig. 2

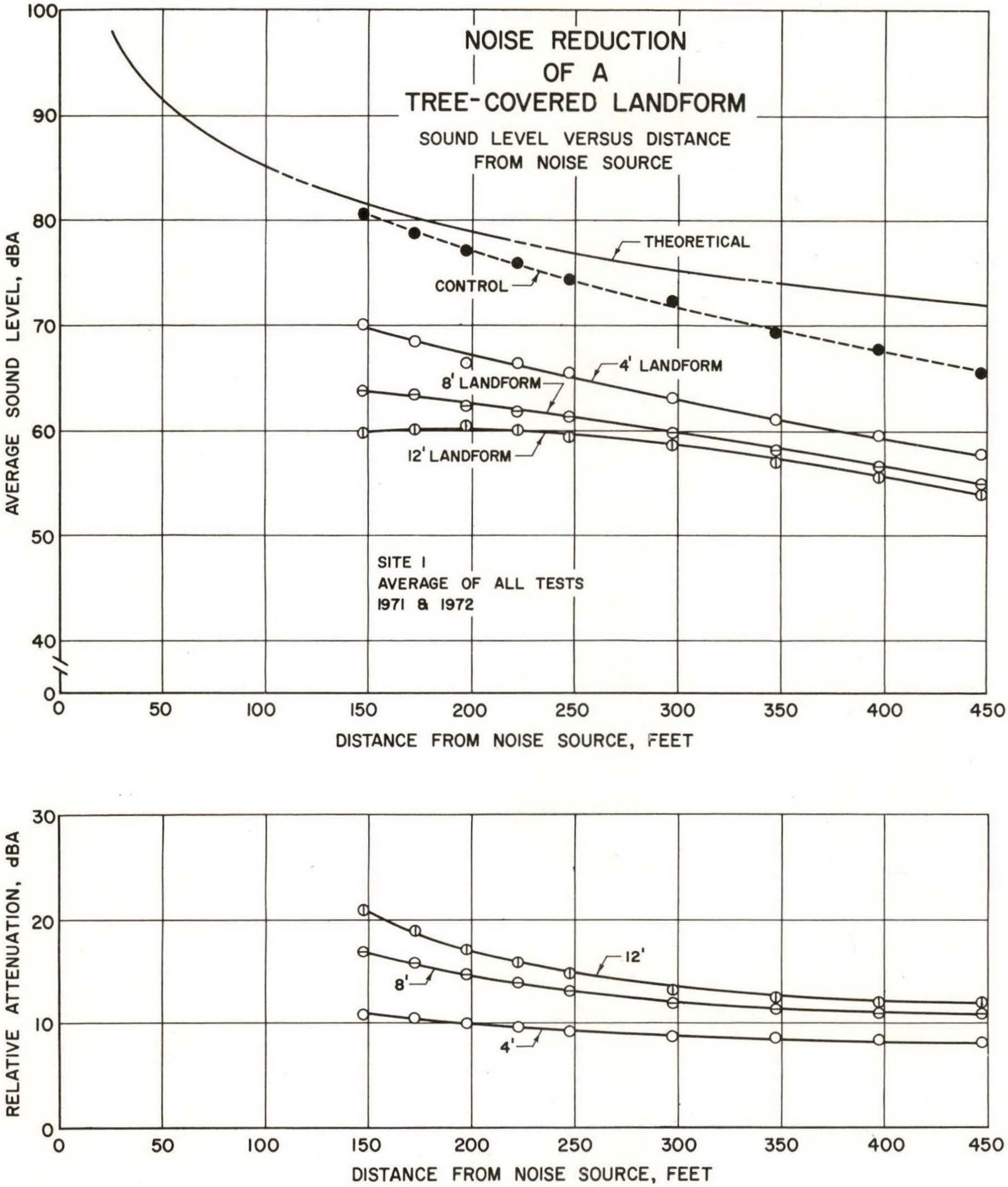
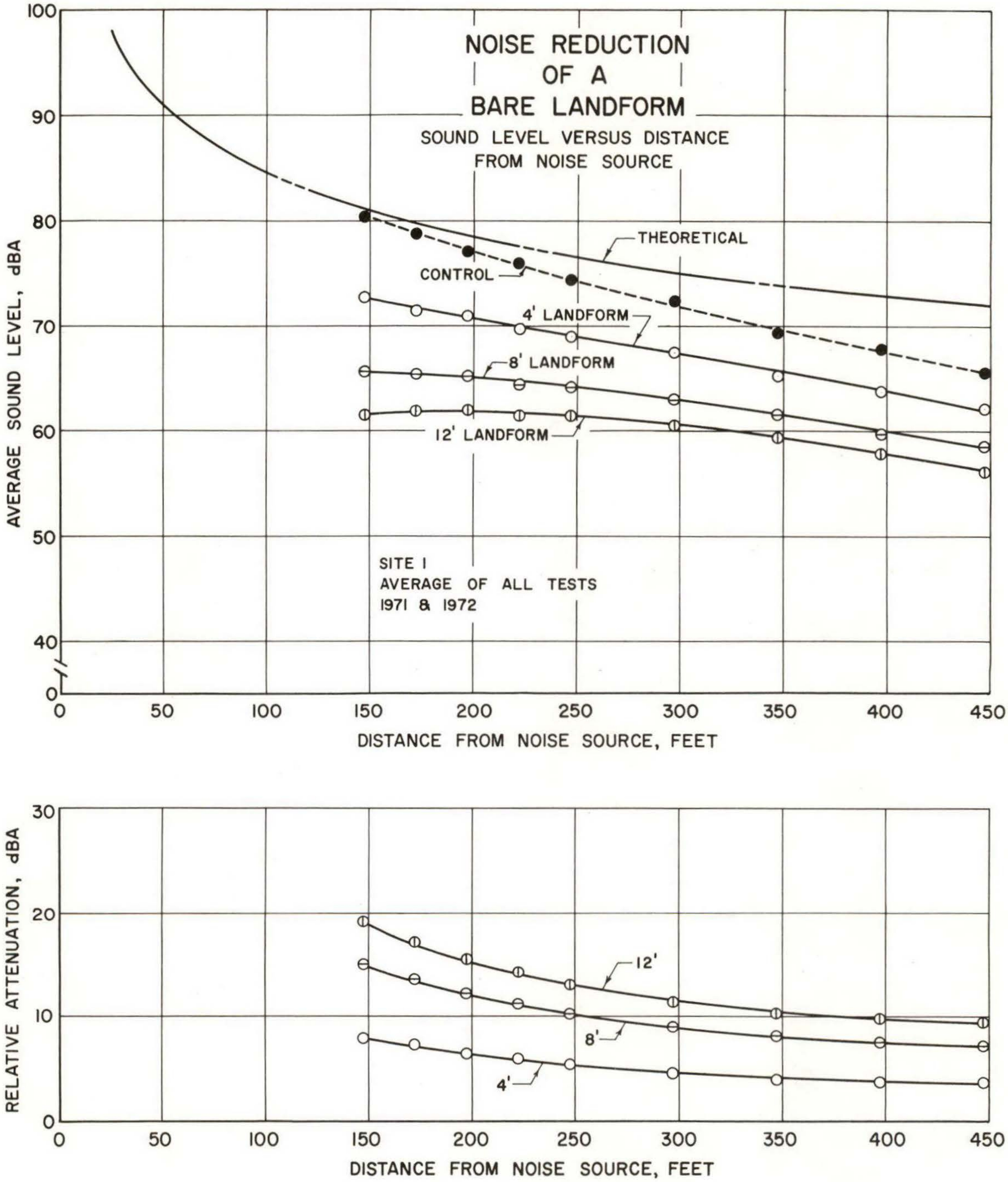
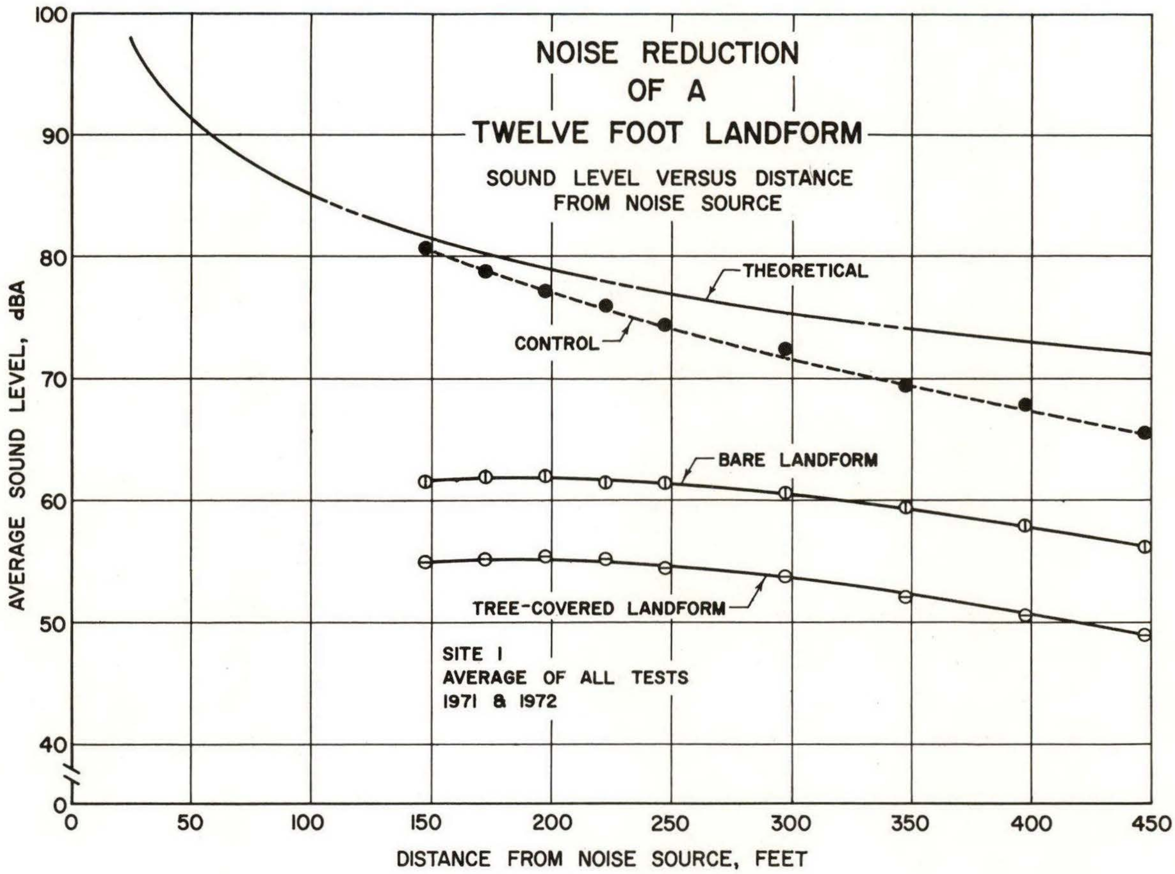

NOISE REDUCTION
OF A
TREE-COVERED LANDFORM
SOUND LEVEL VERSUS DISTANCE
FROM NOISE SOURCE
THEORETICAL
CONTROL
4' LANDFORM
8' LANDFORM
12' LANDFORM
SITE I
AVERAGE OF ALL TESTS
1971 & 1972
AVERAGE SOUND LEVEL, dBA
DISTANCE FROM NOISE SOURCE, FEET
12'
8'
4'
RELATIVE ATTENUATION, dBA
DISTANCE FROM NOISE SOURCE, FEET

Fig. 3



NOISE REDUCTION
OF A
BARE LANDFORM
SOUND LEVEL VERSUS DISTANCE
FROM NOISE SOURCE
THEORETICAL
CONTROL
4' LANDFORM
8' LANDFORM
12' LANDFORM
SITE I
AVERAGE OF ALL TESTS
1971 & 1972
AVERAGE SOUND LEVEL, dBA
DISTANCE FROM NOISE SOURCE, FEET
12'
8'
4'
RELATIVE ATTENUATION, dBA
DISTANCE FROM NOISE SOURCE, FEET

Fig. 4


NOISE REDUCTION
OF A
TWELVE FOOT LANDFORM
SOUND LEVEL VERSUS DISTANCE
FROM NOISE SOURCE
THEORETICAL
CONTROL
BARE LANDFORM
TREE-COVERED LANDFORM
SITE I
AVERAGE OF ALL TESTS
1971 & 1972
AVERAGE SOUND LEVEL, dBA
DISTANCE FROM NOISE SOURCE, FEET
0
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450

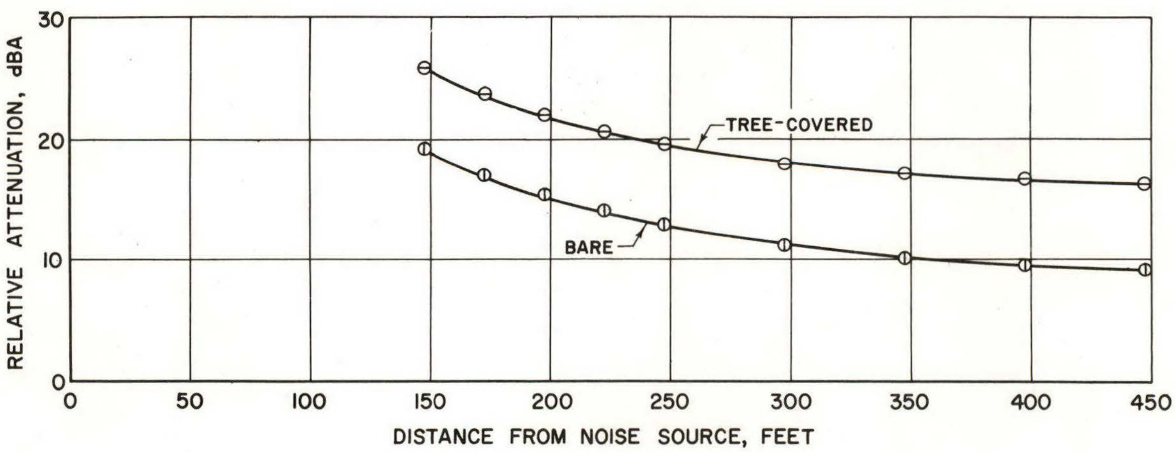

TREE-COVERED
BARE
RELATIVE ATTENUATION, dBA
DISTANCE FROM NOISE SOURCE, FEET
0
10
20
30
0
50
100
150
200
250
300
350
400
450

Fig. 5

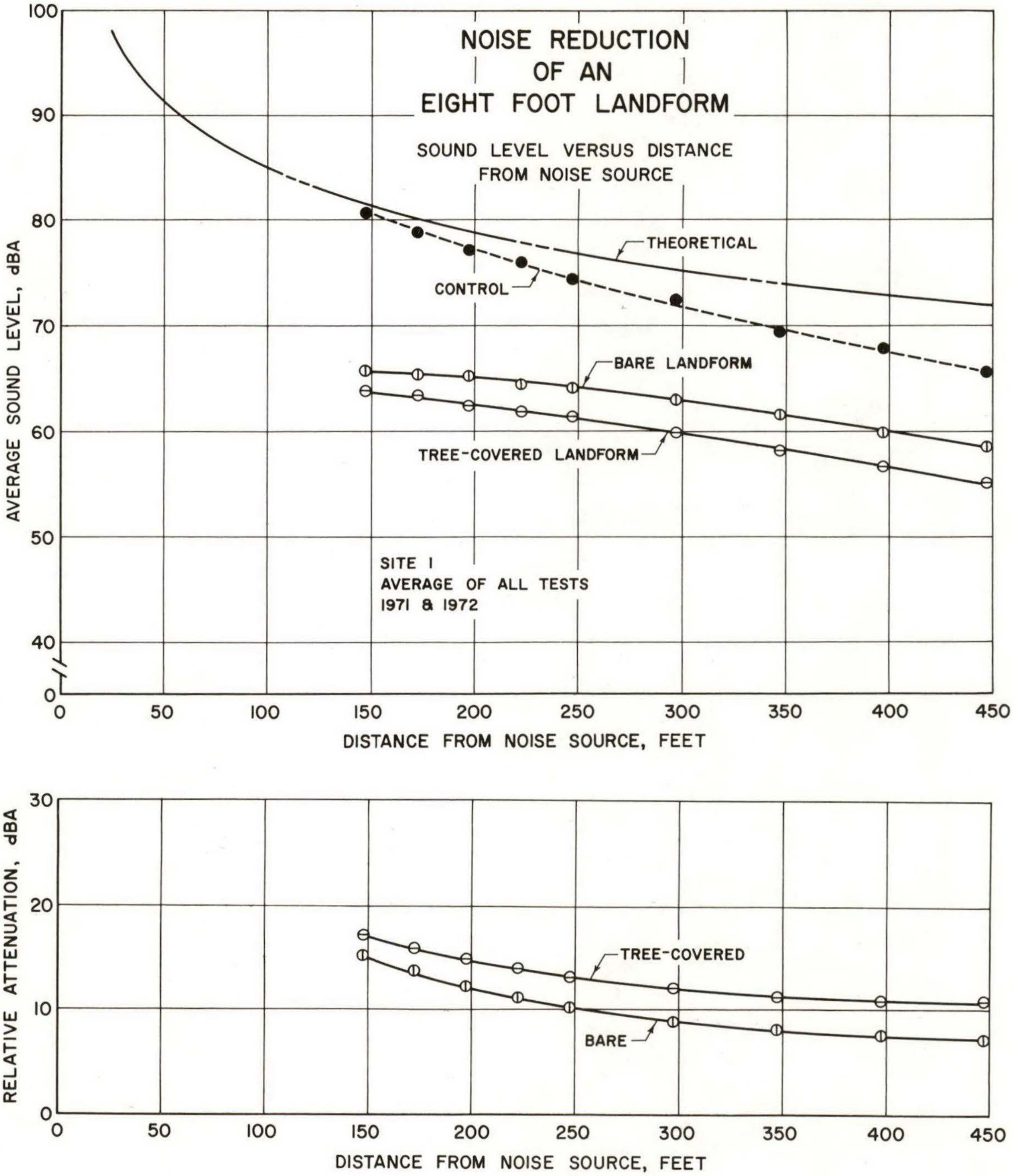

NOISE REDUCTION OF AN EIGHT FOOT LANDFORM
SOUND LEVEL VERSUS DISTANCE FROM NOISE SOURCE
THEORETICAL
CONTROL
BARE LANDFORM
TREE-COVERED LANDFORM
SITE I
AVERAGE OF ALL TESTS
1971 & 1972
AVERAGE SOUND LEVEL, dBA
DISTANCE FROM NOISE SOURCE, FEET
0
50
100
150
200
250
300
350
400
450
40
50
60
70
80
90
100
TREE-COVERED
BARE
RELATIVE ATTENUATION, dBA
10
20
30

Fig. 6

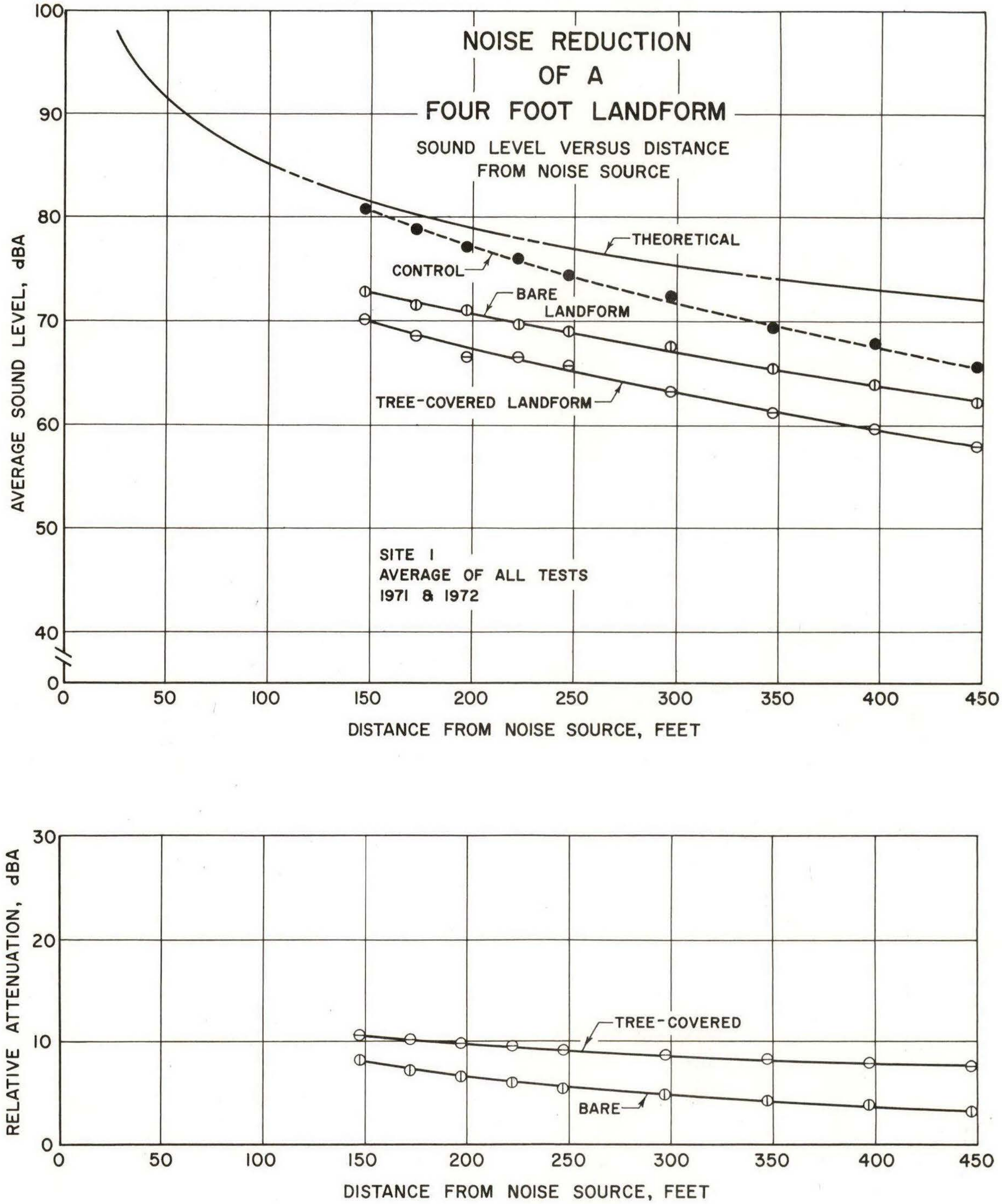

NOISE REDUCTION
OF A
FOUR FOOT LANDFORM
SOUND LEVEL VERSUS DISTANCE
FROM NOISE SOURCE
THEORETICAL
CONTROL
BARE
LANDFORM
TREE-COVERED LANDFORM
SITE I
AVERAGE OF ALL TESTS
1971 & 1972
AVERAGE SOUND LEVEL, dBA
DISTANCE FROM NOISE SOURCE, FEET
0
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450
TREE-COVERED
BARE
RELATIVE ATTENUATION, dBA
0
10
20
30
DISTANCE FROM NOISE SOURCE, FEET

Fig. 7

is also shown. The theoretical curve is shown for reference only, and is a plot of the equation $S_d = S_o - 20 \log \frac{d}{d_o}$, where d is the prescribed distance from the noise source, d_o is the reference distance where the sound level is known, S_d is the calculated sound level (dBA) at the prescribed distance from the noise source, and S_o is the sound level (dBA) at the reference distance.

ORIGINAL "LIVE" SOUND TESTS

The original "live" sound of passing trucks was used at site 1 for one series of tests, to make a comparison with the tape-recorded sound. Sound level meters were set up behind the tree-covered land-form, bare land-form, and open area, and maximum sound level readings were recorded for an individual truck as it passed by each meter. The procedure was repeated at varying distances behind the belt. Measurements of six trucks were made at each distance, and averaged. These average values are shown in Fig. 8.

To complete the "live" sound tests we made measurements behind the trees alone (no land-form), and combined this data with that of the preceding tests, using relative attenuation curves (Fig. 9), to compare the noise-reducing properties of the three media studied.

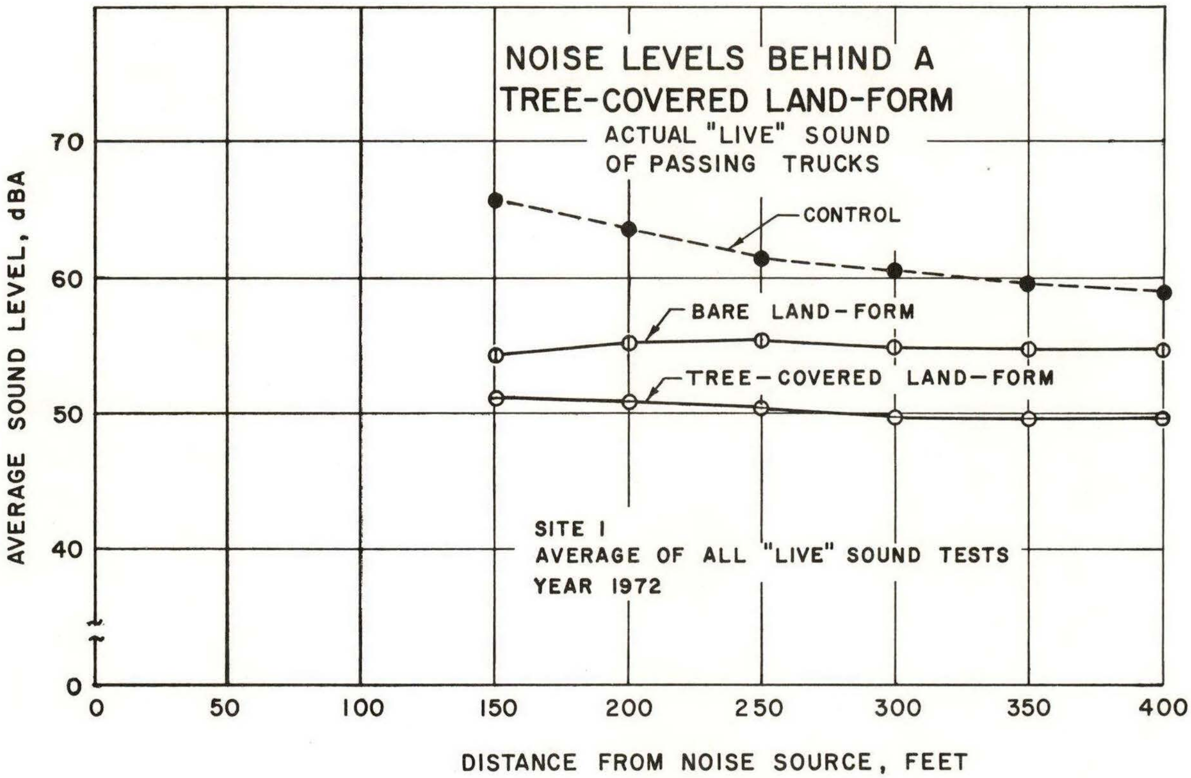

NOISE LEVELS BEHIND A
TREE-COVERED LAND-FORM
ACTUAL "LIVE" SOUND
OF PASSING TRUCKS
CONTROL
BARE LAND-FORM
TREE-COVERED LAND-FORM
SITE I
AVERAGE OF ALL "LIVE" SOUND TESTS
YEAR 1972
AVERAGE SOUND LEVEL, dBA
70
60
50
40
0
0
50
100
150
200
250
300
350
400
DISTANCE FROM NOISE SOURCE, FEET

Fig. 8

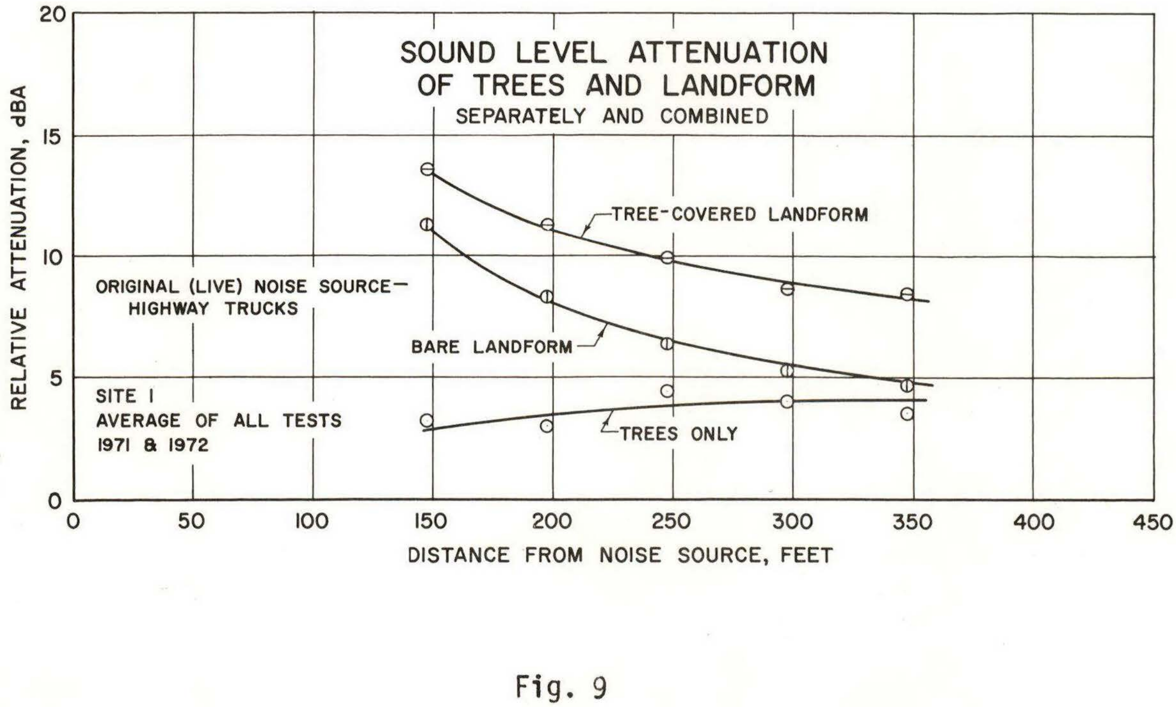

SOUND LEVEL ATTENUATION
OF TREES AND LANDFORM
SEPARATELY AND COMBINED
TREE-COVERED LANDFORM
ORIGINAL (LIVE) NOISE SOURCE—
HIGHWAY TRUCKS
BARE LANDFORM
SITE I
AVERAGE OF ALL TESTS
1971 & 1972
TREES ONLY
RELATIVE ATTENUATION, dBA
20
15
10
5
0
0
50
100
150
200
250
300
350
400
450
DISTANCE FROM NOISE SOURCE, FEET

Fig. 9

OCTAVE BAND ANALYSIS

Noise screening properties of the site 1 tree and land-form combinations were studied by octave band analysis. Sound levels at selected positions in the field of measurement were recorded on magnetic tape, and the tape was analyzed in standard octave band widths having center frequencies of 63, 125, 250, 500, 1000, 2000 and 4000 Hz. Graphs which indicate band width levels also include a "flat" or unweighted curve and

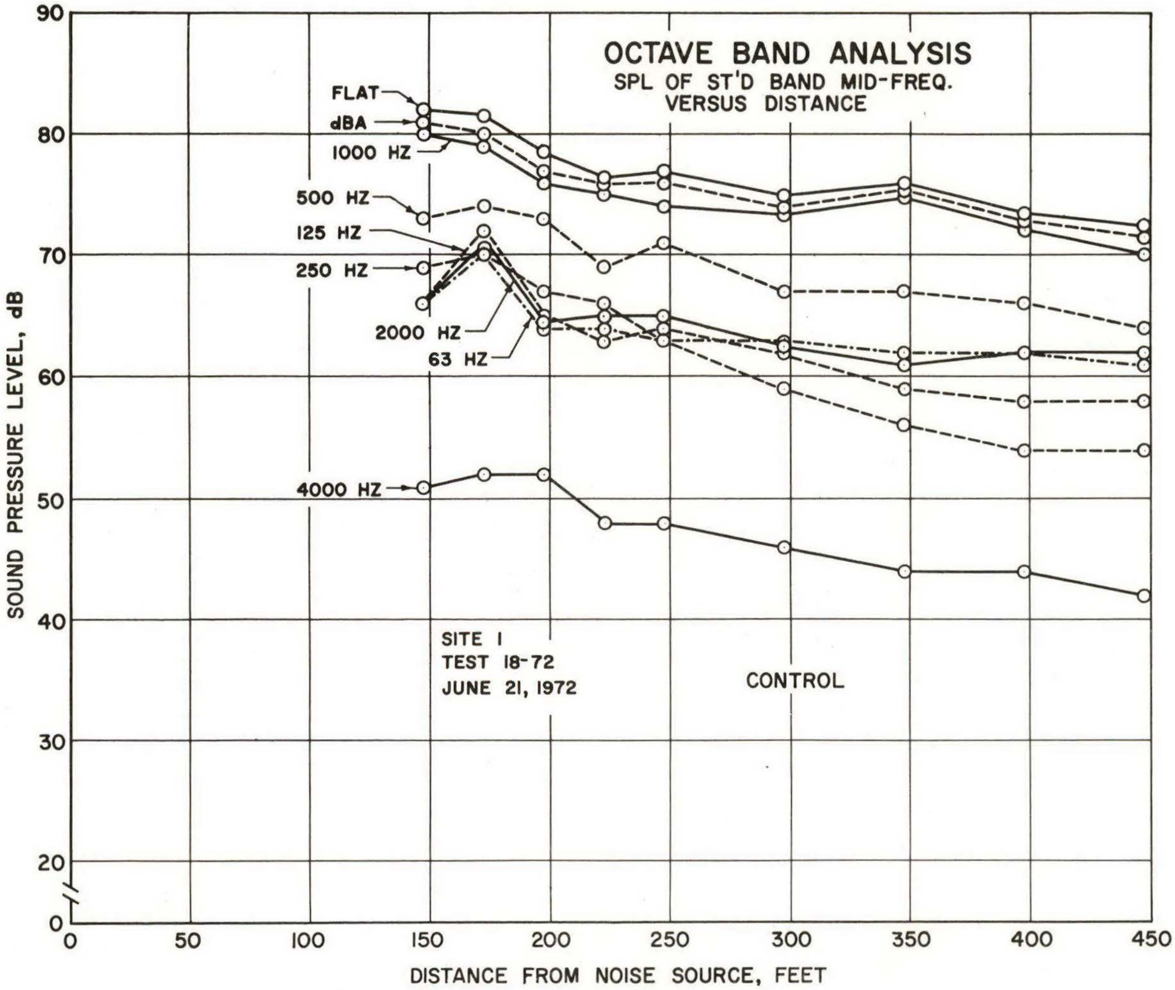


Fig. 10

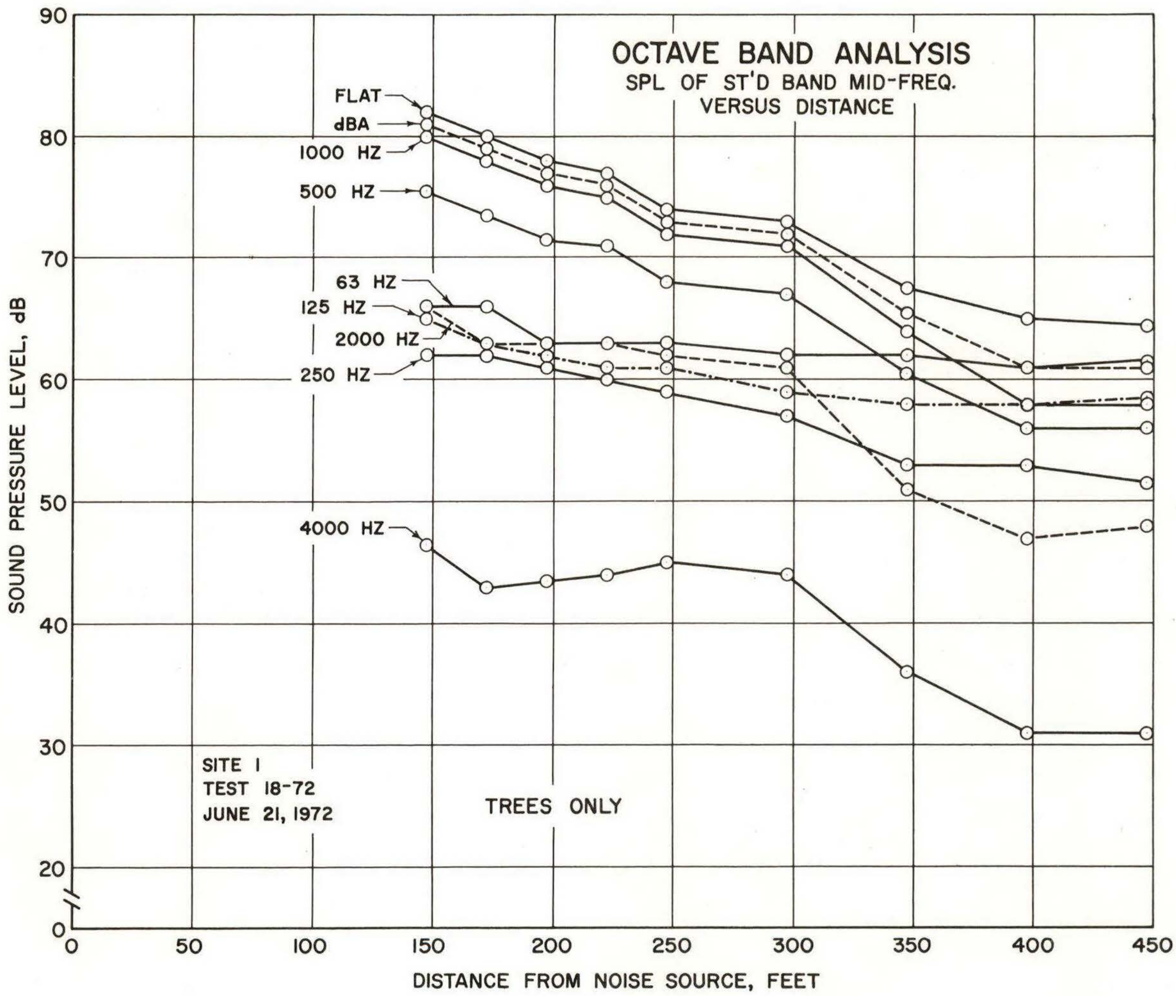

OCTAVE BAND ANALYSIS
SPL OF ST'D BAND MID-FREQ.
VERSUS DISTANCE
FLAT
dBA
1000 HZ
500 HZ
63 HZ
125 HZ
2000 HZ
250 HZ
4000 HZ
SITE I
TEST 18-72
JUNE 21, 1972
TREES ONLY
SOUND PRESSURE LEVEL, dB
DISTANCE FROM NOISE SOURCE, FEET
90
80
70
60
50
40
30
20
0
0
50
100
150
200
250
300
350
400
450

Fig. 11

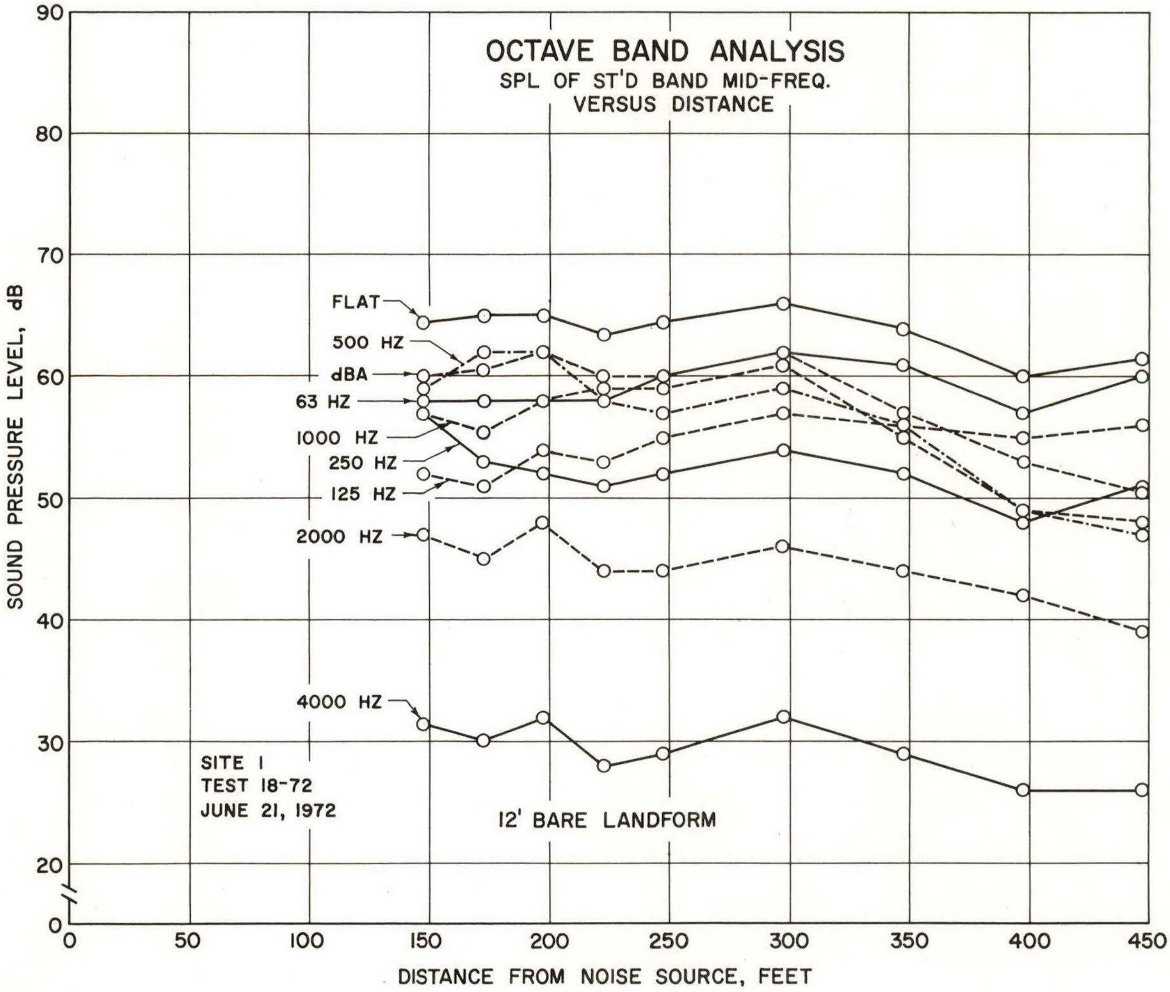

OCTAVE BAND ANALYSIS
SPL OF ST'D BAND MID-FREQ.
VERSUS DISTANCE
SOUND PRESSURE LEVEL, dB
DISTANCE FROM NOISE SOURCE, FEET
FLAT
500 HZ
dBA
63 HZ
1000 HZ
250 HZ
125 HZ
2000 HZ
4000 HZ
SITE I
TEST 18-72
JUNE 21, 1972
12' BARE LANDFORM
0
50
100
150
200
250
300
350
400
450
20
30
40
50
60
70
80
90

Fig. 12

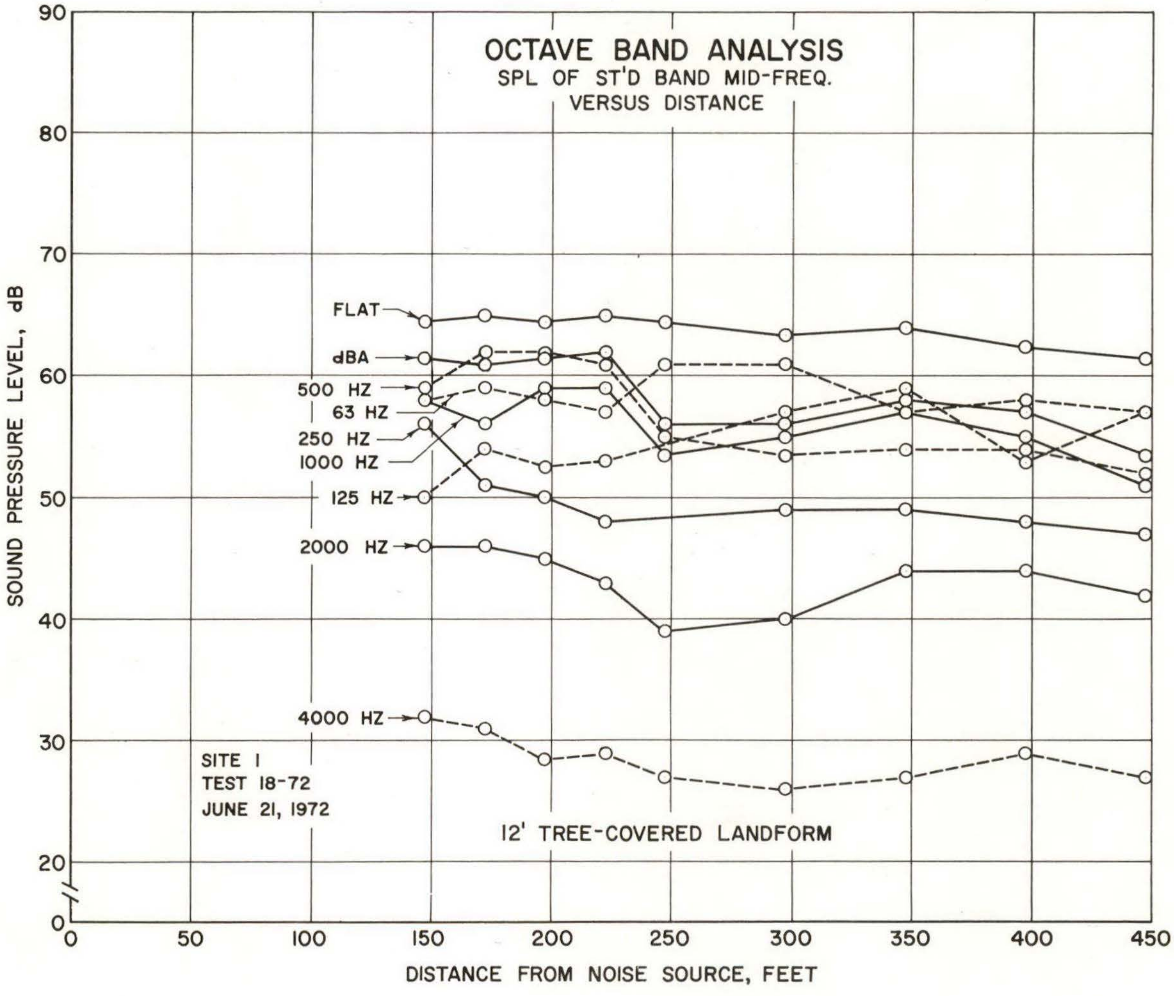

OCTAVE BAND ANALYSIS
SPL OF ST'D BAND MID-FREQ.
VERSUS DISTANCE
FLAT
dBA
500 HZ
63 HZ
250 HZ
1000 HZ
125 HZ
2000 HZ
4000 HZ
SITE I
TEST 18-72
JUNE 21, 1972
12' TREE-COVERED LANDFORM
SOUND PRESSURE LEVEL, dB
DISTANCE FROM NOISE SOURCE, FEET
0
20
30
40
50
60
70
80
90
0
50
100
150
200
250
300
350
400
450

Fig. 13

a dBA weighted curve (Fig. 10 to 13). Graphs are shown for "control", trees-only, 12' bare land-form and 12' tree-covered land-form tests.

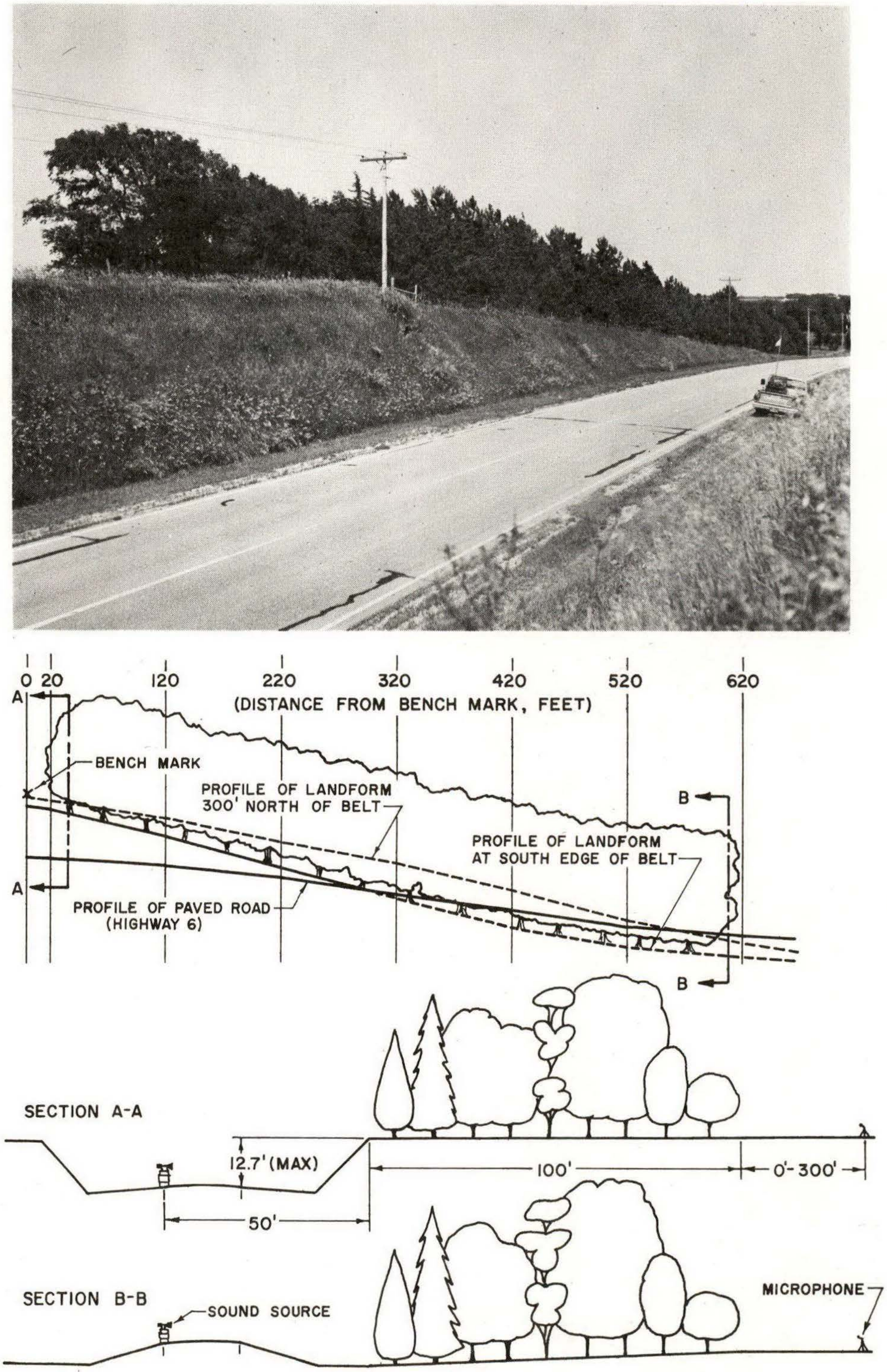
These graphs have been included for the benefit of those who may wish to make a detailed examination of the "frequency effect" in noise transmission; no attempt has been made to explain the characteristics of this analysis, as such is beyond the intent of this study.

SITE 2 - MILFORD HIGHWAY CUT - WEST

This site was located on U. S. 34 highway, four miles northeast of Milford, Nebraska. The configuration of the cross-section gradually changed from a 12-foot-deep cut to a 4-foot-high fill. This change, together with the 100-foot-wide belt of trees lining the highway, provided the desired variables for the study. A meadow adjacent to the belt served as a control surface area. Figure 14 illustrates the terrain at this site, showing the grade profile both at the belt and 300 feet behind it. Figure 15 includes a contour map, showing the topography behind the belt, where sound measurements were made, and a photograph of the control test area.

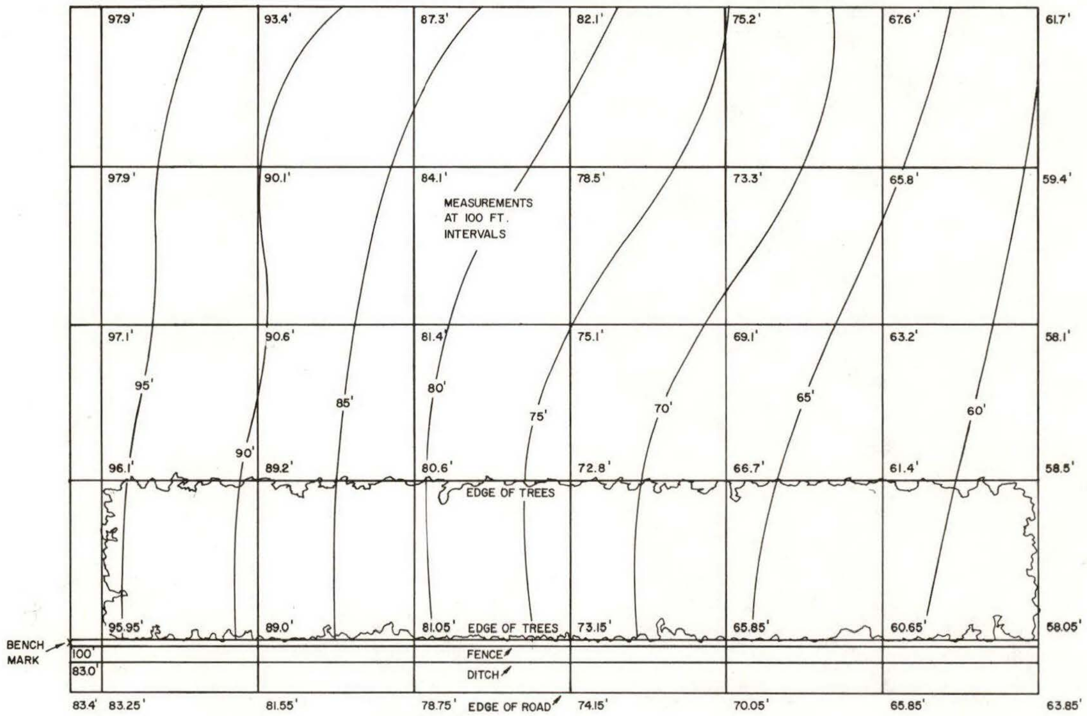
Tape-recorded truck noise was used exclusively at this site, and the sound source was placed 50 feet in front of the belt. The receiving microphone was placed at distances varying from zero to 300 feet from the rear edge of the belt. The noise reduction characteristics of the belt are illustrated in Figure 16. These include a theoretical curve calculated from a point source sound propagation equation, a control surface curve, and a tree land-form combination curve for each depth of cut (or height of fill) studied. These curves illustrate the effect of tree-covered land-forms of different heights on noise reduction, and

give some indication of the acoustical effect of an elevated highway.



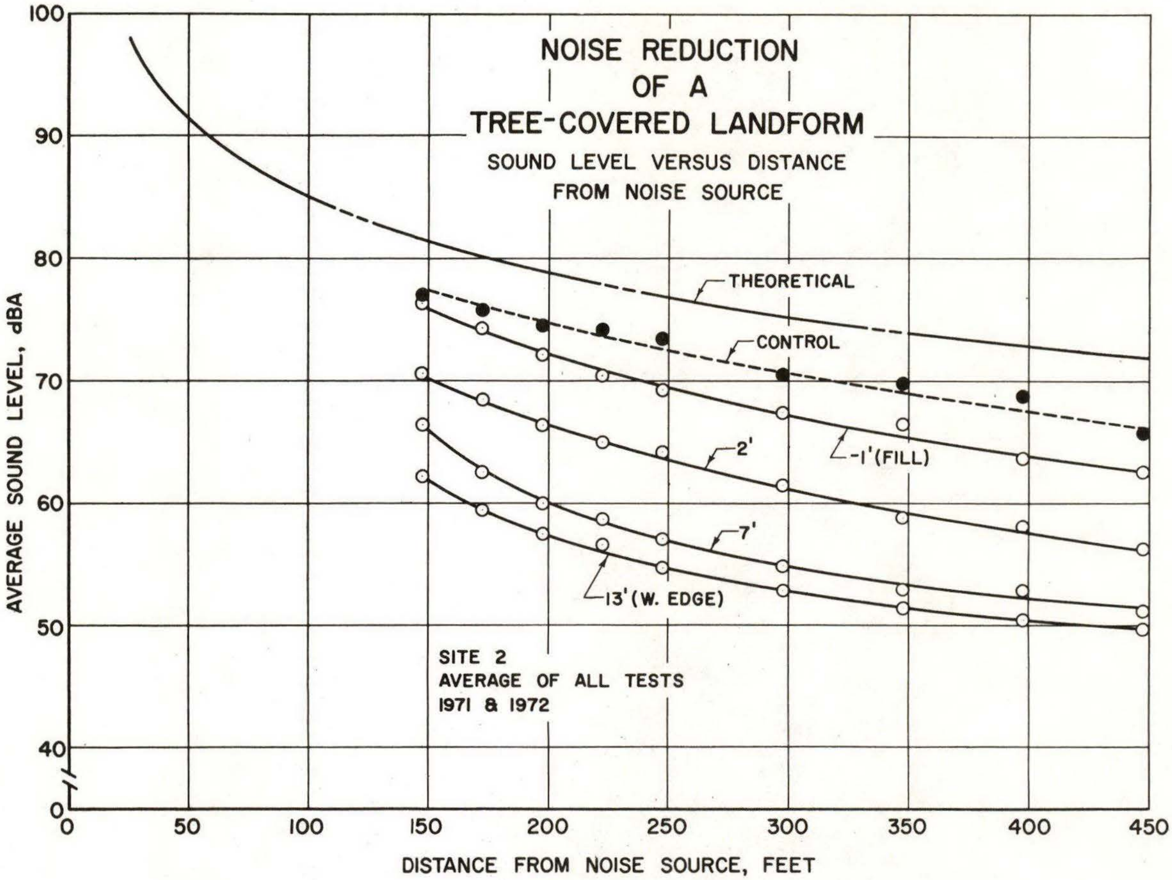
PROFILE AND SECTIONS OF SITE 2

Fig. 14



PLAN, SITE 2

Fig. 15


NOISE REDUCTION
OF A
TREE-COVERED LANDFORM
SOUND LEVEL VERSUS DISTANCE
FROM NOISE SOURCE
THEORETICAL
CONTROL
2'
-1'(FILL)
7'
13'(W. EDGE)
SITE 2
AVERAGE OF ALL TESTS
1971 & 1972
AVERAGE SOUND LEVEL, dBA
DISTANCE FROM NOISE SOURCE, FEET

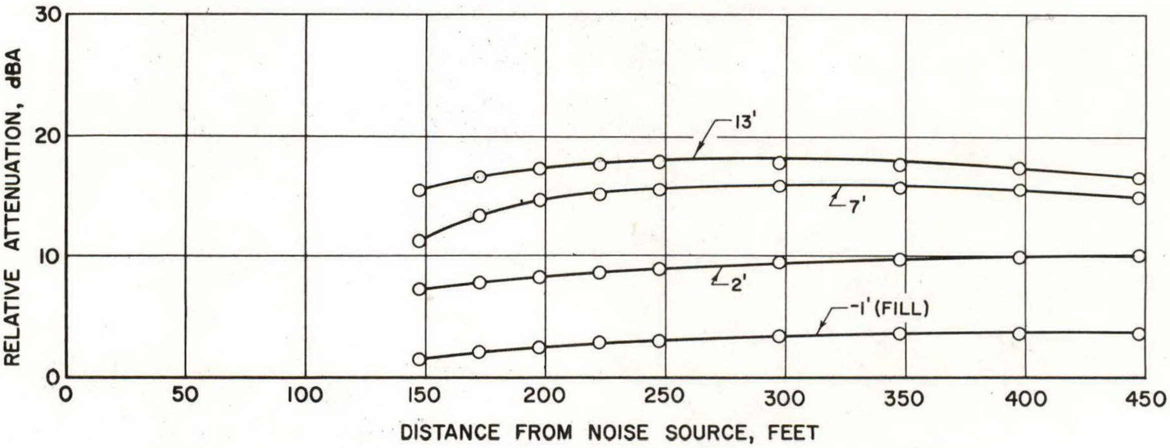

13'
7'
2'
-1'(FILL)
RELATIVE ATTENUATION, dBA
DISTANCE FROM NOISE SOURCE, FEET

Fig. 16

SITE 3 - MILFORD HIGHWAY CUT - EAST

This site was located a few hundred feet east of site 2, and was similar to it in most respects. The tree belt was of the same composition and age, although not in as good condition. The maximum depth of cut was about 10 feet. The photograph (Figure 17) illustrates the tree structure of the belt. Figure 18, which includes the profile, section, and contour map, shows the grade profile at the belt and the topography behind it, which, as may be noted, was somewhat different from the site 2 topography, illustrated in Fig. 15. The same control surface area was used for both belts and the same sound projection procedure was followed.

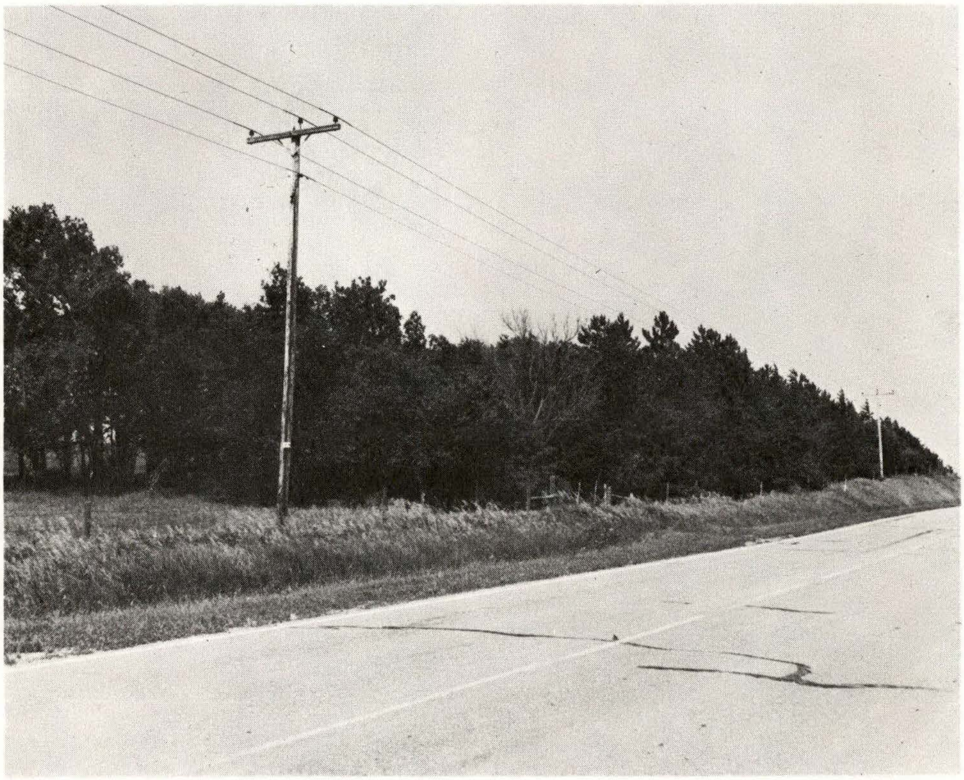
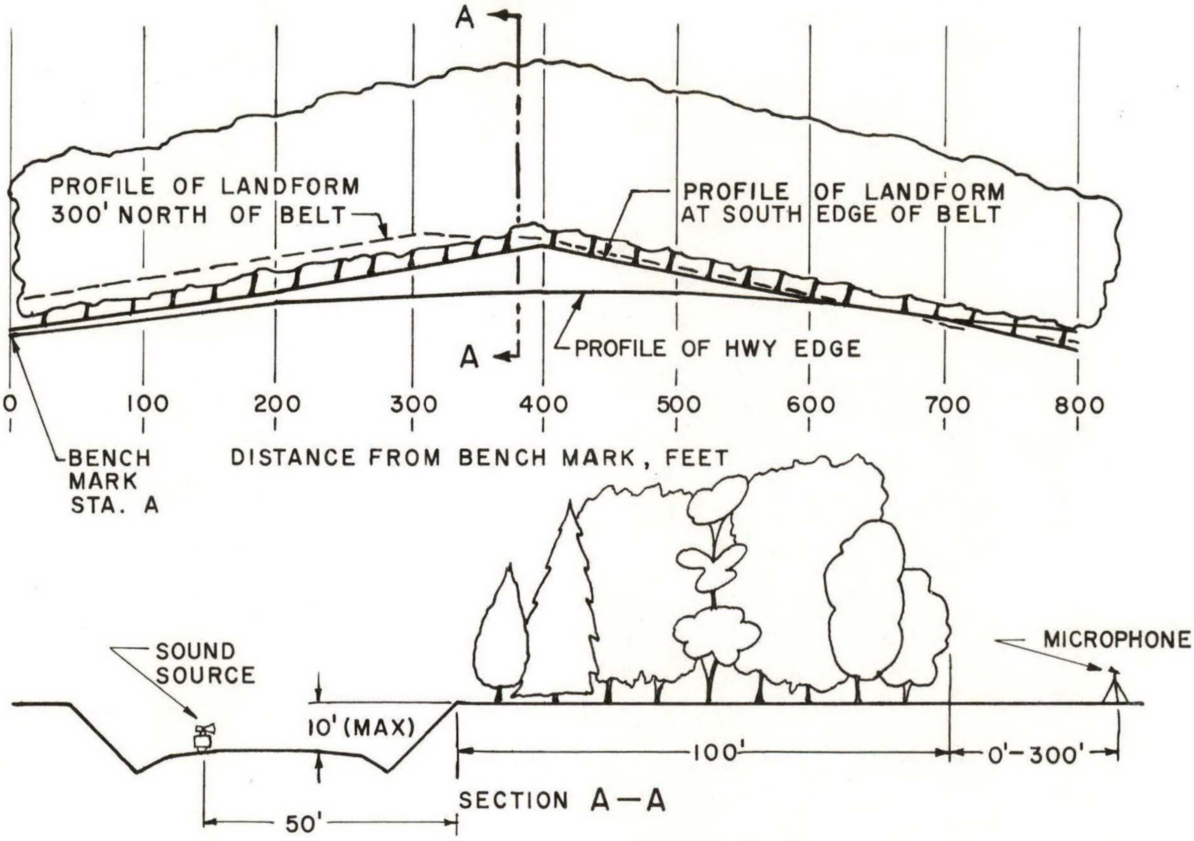
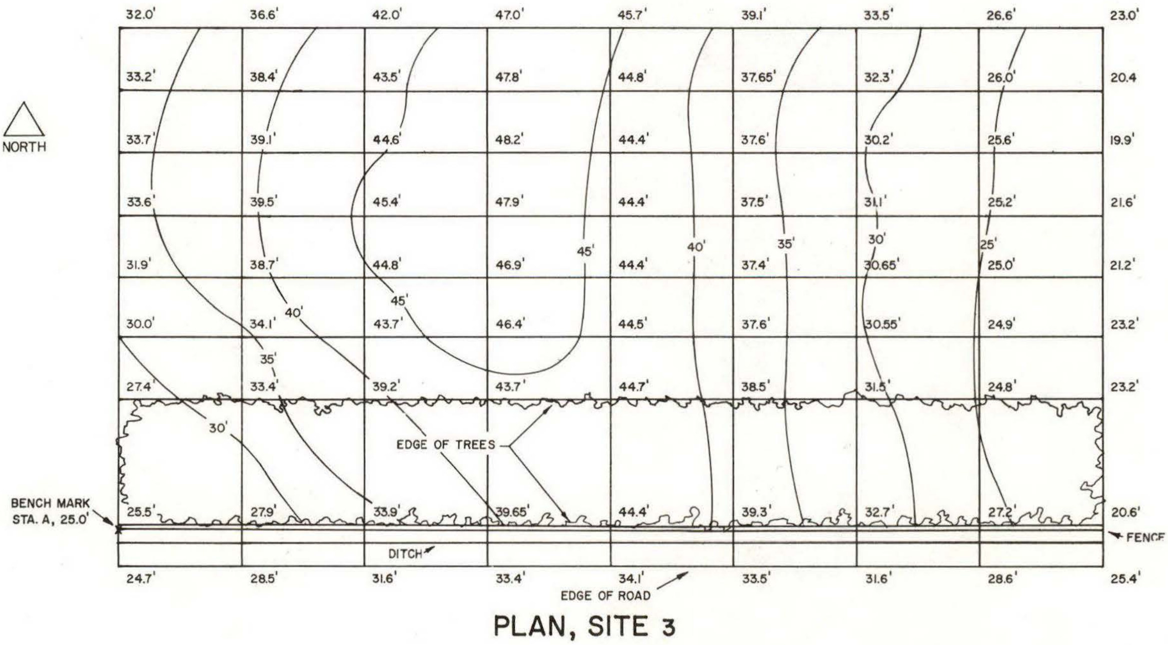


Fig. 17



PROFILE AND SECTION OF SITE 3



PLAN, SITE 3

Fig. 18

The noise reduction characteristics of the belt are illustrated in Fig. 19, which includes the theoretical curve, control surface curve and tree land-form combination curves as in the corresponding site 2 graph of Fig. 16.

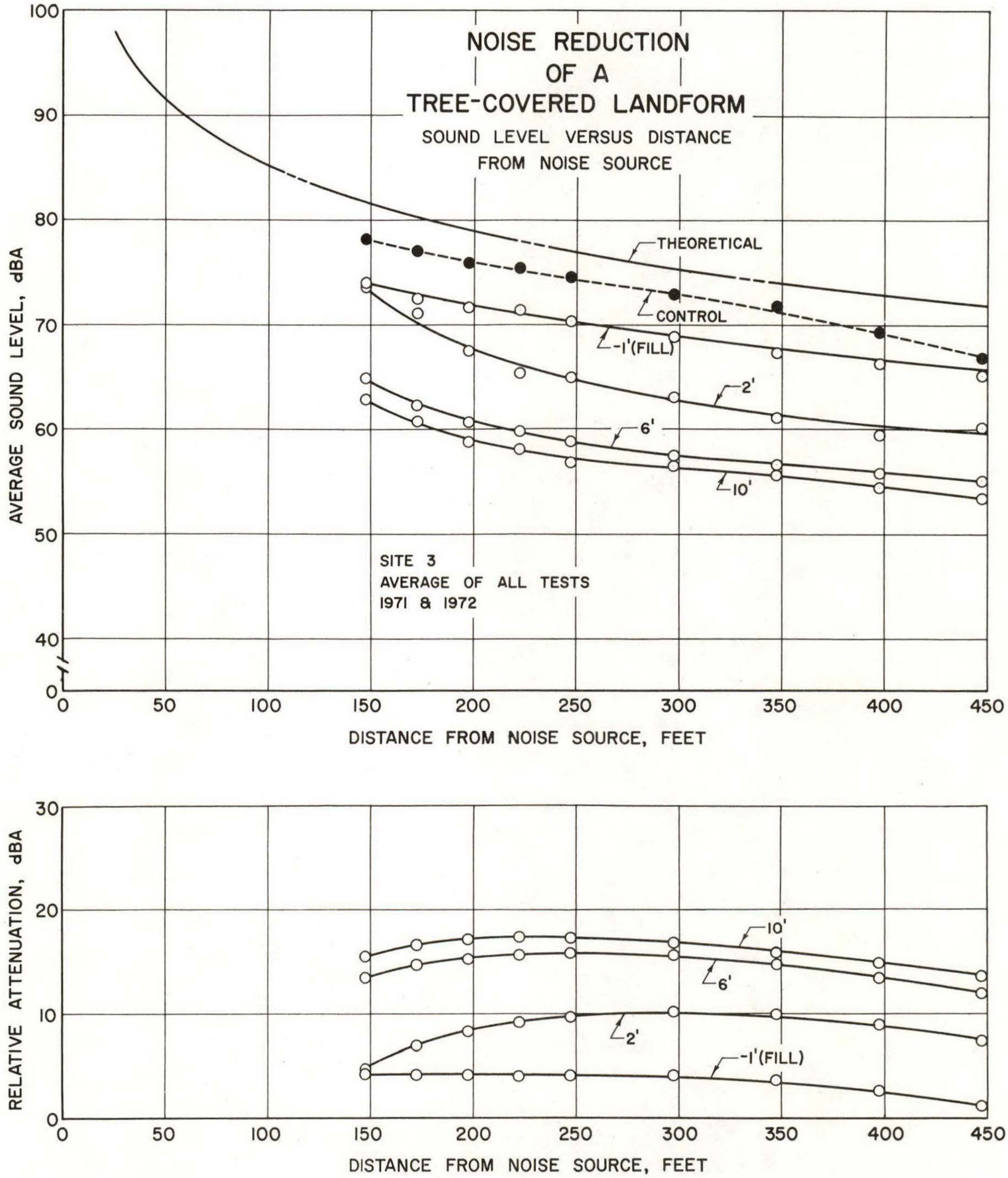
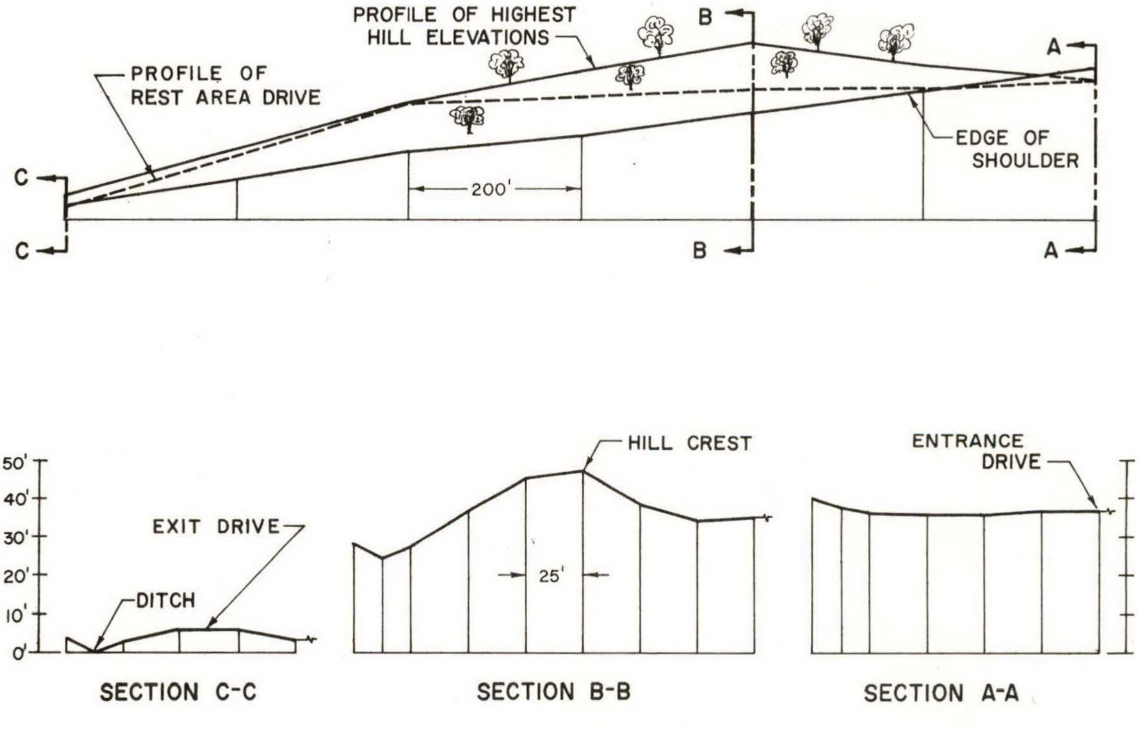


Fig. 19

SITE 4 I-80 REST AREA

This site was selected for study because of its location and ground configuration. There were no trees of significant size at this site, so the results of the tests were useful, within the intent of the study, mainly for reference purposes. The 20-foot-high hill located between the near traffic lane and adjacent rest area served as the land-form. The photograph of Figure 20 is a view looking toward the hill from the entrance drive, and shows a truck on I-80 and the rest area on the opposite side of the hill. Truck traffic served as the noise source at this site. The profile and sections of Figure 20 illustrated the ground configuration at the entrance drive, exit drive, and highest point of the hill, which was nearly opposite the rest area main building. Sound level measurements were made at the rest area entrance and exit drives where the ground surface was nearly level, and at several positions behind the protective hill, all at the same distance from the highway edge. Noise levels of twelve individual trucks were measured at each position, and readings were averaged. Eight tests made during the summers of 1971 and 1972 were then combined, to give the results illustrated in Figures 21 and 22. The curves compare sound levels measured behind the grass-covered hill with those measured near the entrance and exit drives. Figure 21 is for the near lane of I-80 and Figure 22 is for the far lane. The lower curves are labeled "Average Relative Attenuation", because they represent the average of the entrance and exit drive sound levels compared to the land-form sound level.



PROFILE AND SECTIONS— SITE 4

Fig. 20

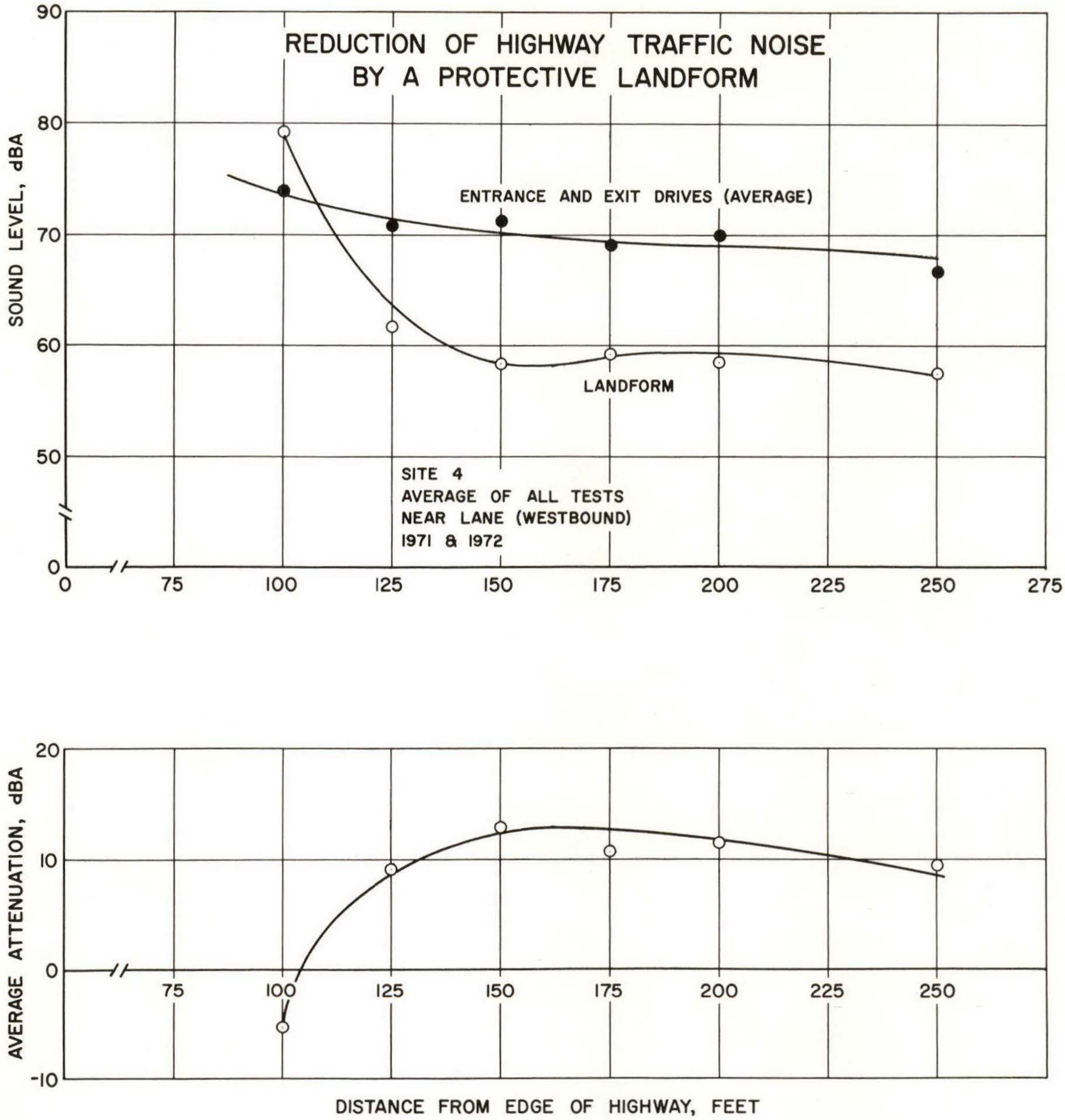
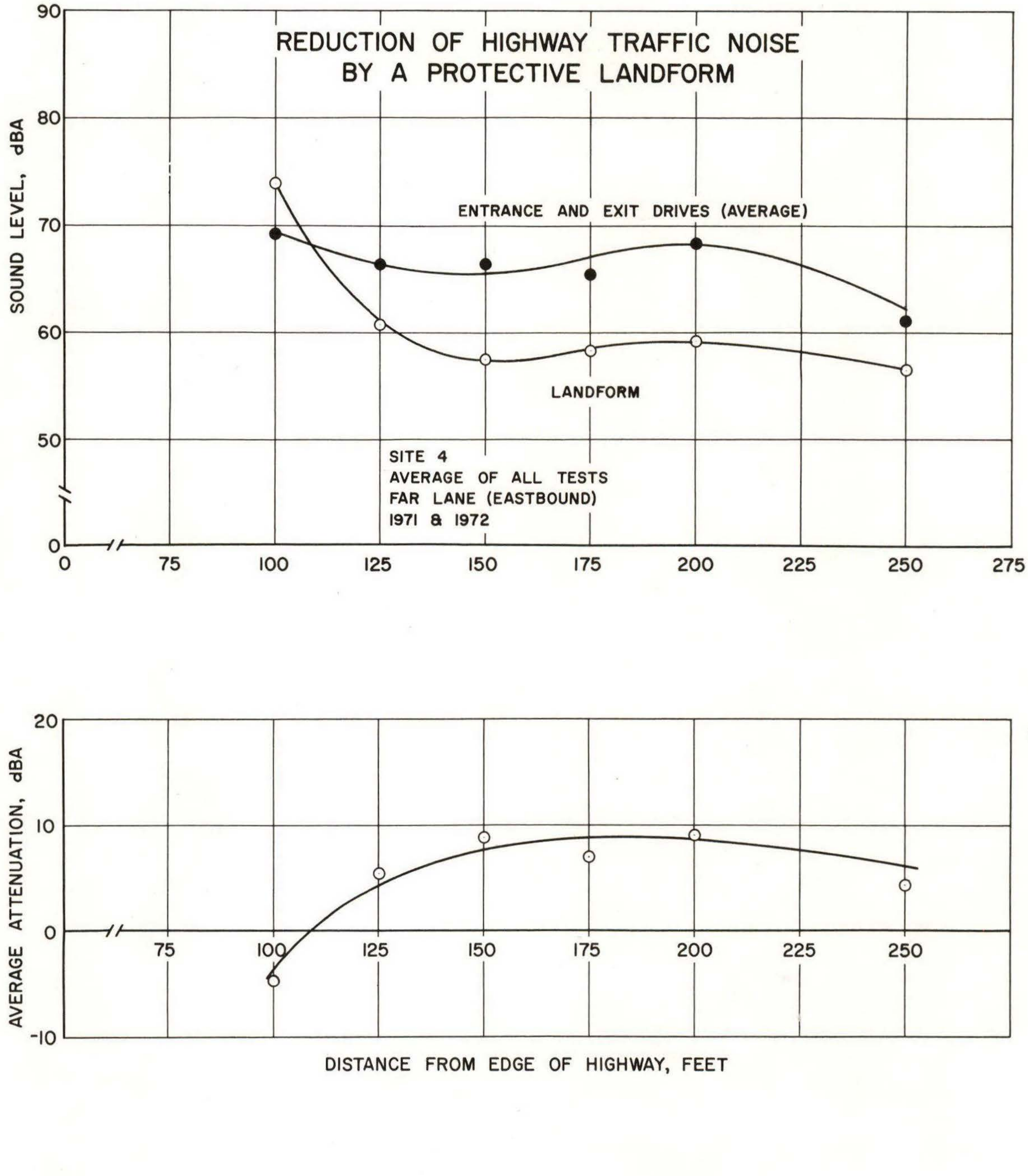

REDUCTION OF HIGHWAY TRAFFIC NOISE
BY A PROTECTIVE LANDFORM
SOUND LEVEL, dBA
90
80
70
60
50
0
ENTRANCE AND EXIT DRIVES (AVERAGE)
LANDFORM
SITE 4
AVERAGE OF ALL TESTS
NEAR LANE (WESTBOUND)
1971 & 1972
0
75
100
125
150
175
200
225
250
275
AVERAGE ATTENUATION, dBA
20
10
0
-10
75
100
125
150
175
200
225
250
DISTANCE FROM EDGE OF HIGHWAY, FEET

Fig. 21



REDUCTION OF HIGHWAY TRAFFIC NOISE
BY A PROTECTIVE LANDFORM
SOUND LEVEL, dBA
90
80
70
60
50
0
ENTRANCE AND EXIT DRIVES (AVERAGE)
LANDFORM
SITE 4
AVERAGE OF ALL TESTS
FAR LANE (EASTBOUND)
1971 & 1972
0
75
100
125
150
175
200
225
250
275
AVERAGE ATTENUATION, dBA
20
10
0
-10
DISTANCE FROM EDGE OF HIGHWAY, FEET

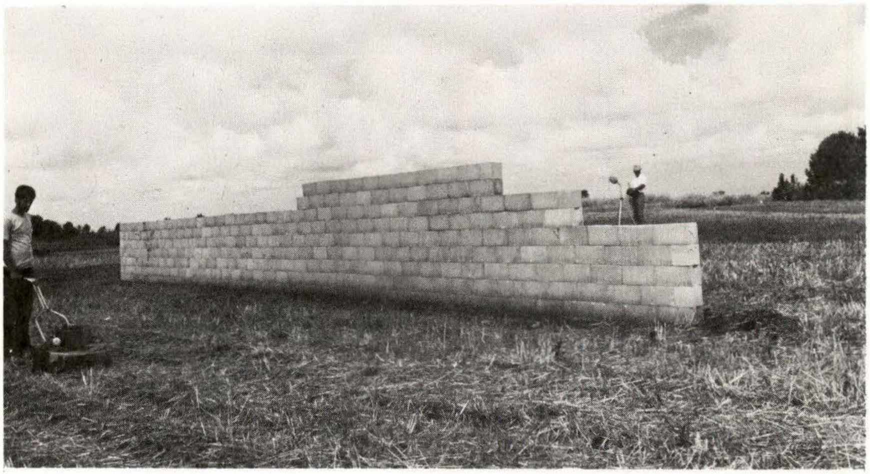
Fig. 22

SITE 5 PLATTSMOUTH TREE-WALL SCREEN

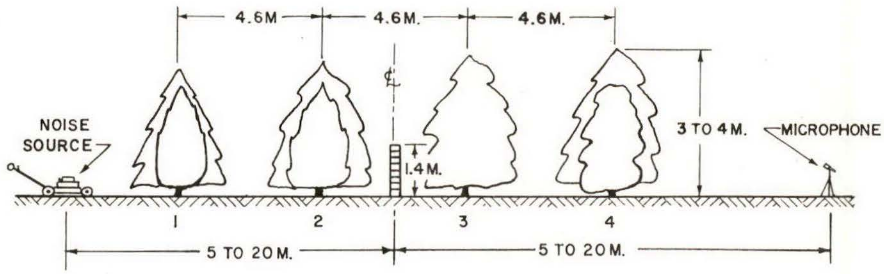
This site was selected for study because of the relatively young trees available on State property under the control of the University of Nebraska. We wanted to simulate an urban noise control situation, where space between the noise source and the protected area might be limited, and where an expeditious solution was desired. The proposed wall and young tree structure could be developed in a relatively short time; and we thought it would perform efficiently in certain situations.

This area of study was somewhat of an addition to the original intended study, and because of time limitations, was not investigated as thoroughly as were the tree and land-form aspects of study. In keeping with the national trend, all units of measurement were reported in the metric system. A power lawnmower provided the noise source, and both microphone positions and source positions were varied. This double variation complicated the measurements somewhat, but yielded more flexible results. Figure 23 includes photographs of the belt and wall structure and a description of the composition of the belt. A segment of the wall was constructed within the belt of trees shown in the upper photo, but is hidden by the trees. A similar segment of the wall was constructed in an "open" area, as shown in the lower photo, where the three wall-heights used in the tests are visible on the right side of the wall. The power lawnmower noise source and the tripod-mounted pick-up-microphone may also be observed in the lower photo.

The lower diagram of the belt and wall structure illustrates the relative placement of trees and wall, and indicates the variable positions of both microphone and noise source. To assure a constant source level, the power mower throttle was set at a fixed position, and the noise



SITE 5
PLATTSMOUTH BELT AND WALL



ROW NO.	NAME OF TREE
1	AUSTRIAN PINE ALTERNATED WITH ROCKY MT. JUNIPER
2	PONDEROSA PINE ALTERNATED WITH EASTERN REDCEDAR
3	SCOTCH PINE
4	AUSTRIAN PINE ALTERNATED WITH ORIENTAL ARBORVITAE

(TREE SPACING IN ALL ROWS – 2 M.)

Fig. 23

level measured with a meter. This level was checked before and after each test series to improve accuracy of measurement. Measurements were made in an open area (control surface), and behind the bare wall section, as well as behind the combined tree and wall section, and behind trees alone. Both source and receiver distances were varied in 5 meter increments. The results of four test runs are illustrated in Fig. 24, Fig. 25 and Fig. 26. Fig. 24 shows typical test results, and illustrates the relative effect of trees alone, wall alone, and tree-and-wall combination in reducing noise levels. The lower attenuation curves aid in making this comparison. These curves are for the full 9-block (1.8 m high) wall.

Fig. 25, which shows attenuation only, illustrates the comparative effect of different wall placements - between noise source and receiver - on the reduction in noise level obtainable. The full 1.8 m wall was used in this test.

Fig. 26 illustrates the comparative effect of different height walls combined with trees in reducing noise levels. A "trees only" curve, which corresponds to zero wall height is also included. The noise source distance for this test was 10 meters in all cases.

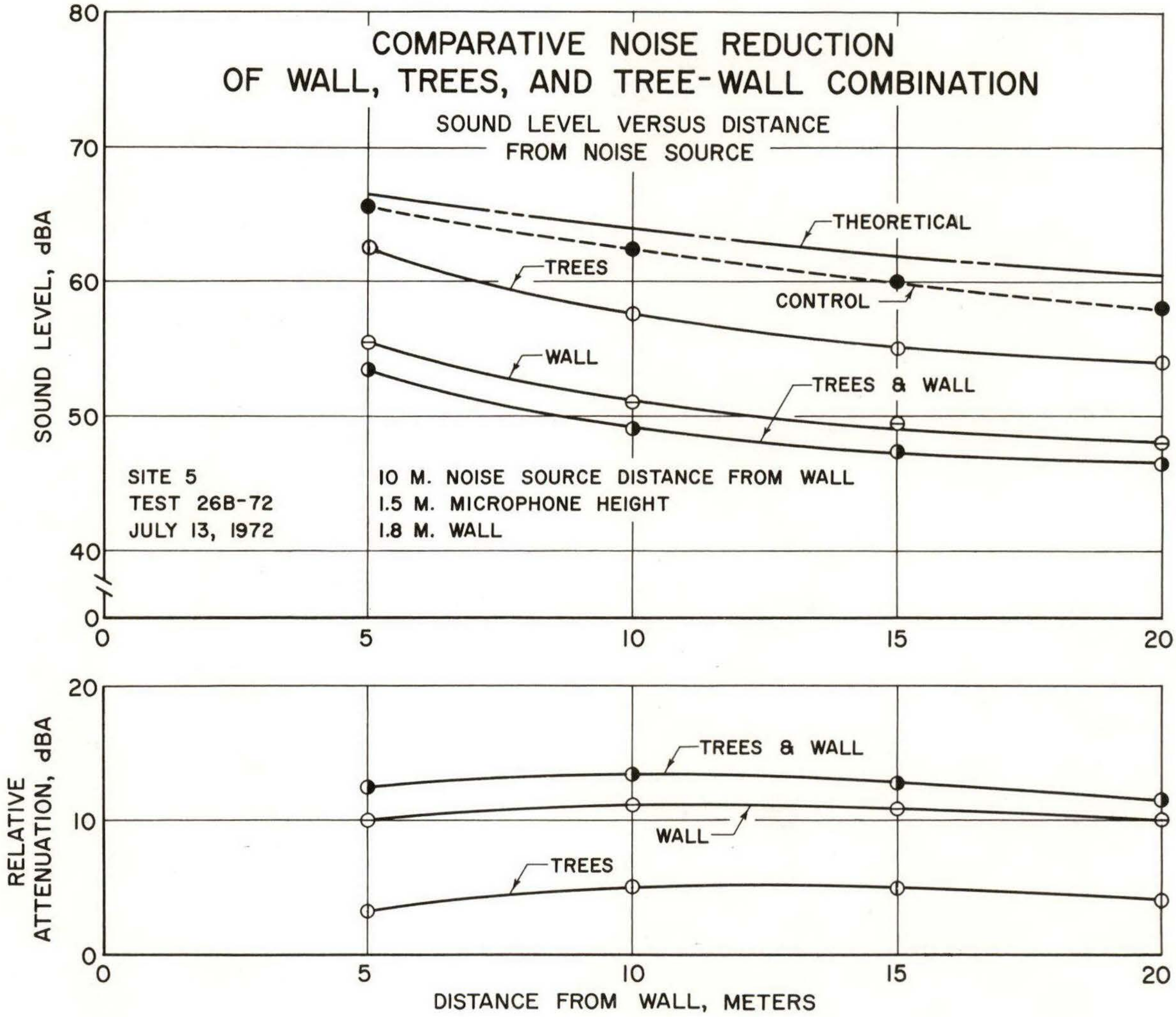

COMPARATIVE NOISE REDUCTION
OF WALL, TREES, AND TREE-WALL COMBINATION
SOUND LEVEL VERSUS DISTANCE
FROM NOISE SOURCE
SOUND LEVEL, dBA
80
70
60
50
40
0
5
10
15
20
THEORETICAL
TREES
CONTROL
WALL
TREES & WALL
SITE 5
TEST 26B-72
JULY 13, 1972
10 M. NOISE SOURCE DISTANCE FROM WALL
1.5 M. MICROPHONE HEIGHT
1.8 M. WALL
RELATIVE ATTENUATION, dBA
20
10
TREES & WALL
WALL
TREES
DISTANCE FROM WALL, METERS

Fig. 24

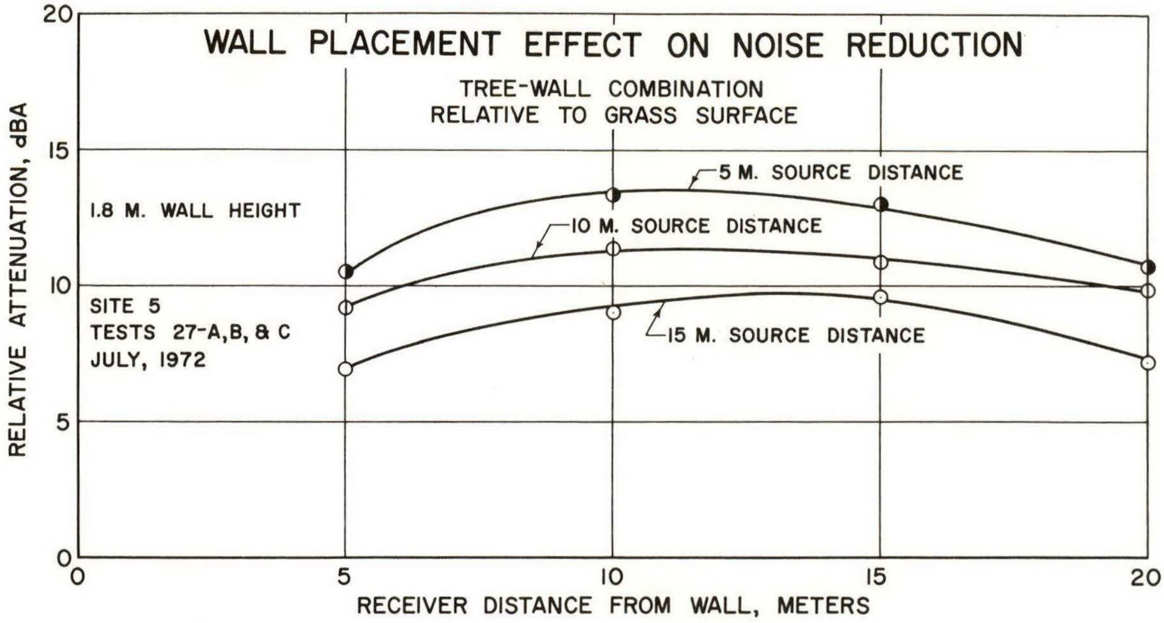

WALL PLACEMENT EFFECT ON NOISE REDUCTION
TREE-WALL COMBINATION
RELATIVE TO GRASS SURFACE
1.8 M. WALL HEIGHT
5 M. SOURCE DISTANCE
10 M. SOURCE DISTANCE
15 M. SOURCE DISTANCE
SITE 5
TESTS 27-A,B, & C
JULY, 1972
RELATIVE ATTENUATION, dBA
RECEIVER DISTANCE FROM WALL, METERS
0
5
10
15
20

Fig. 25

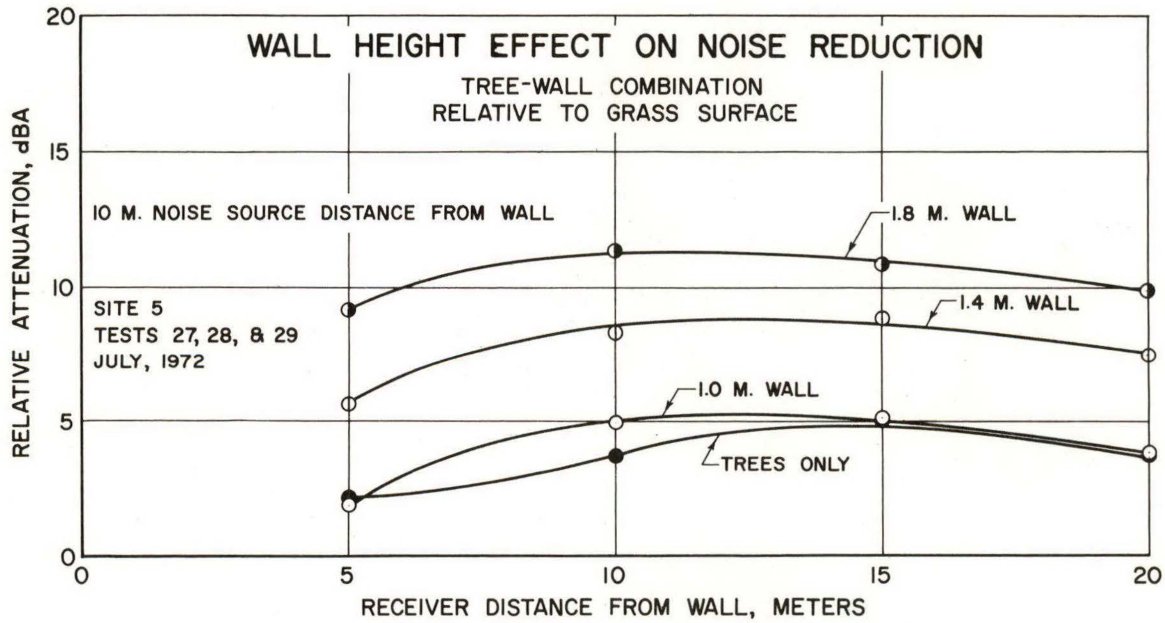

WALL HEIGHT EFFECT ON NOISE REDUCTION
TREE-WALL COMBINATION
RELATIVE TO GRASS SURFACE
10 M. NOISE SOURCE DISTANCE FROM WALL
1.8 M. WALL
1.4 M. WALL
1.0 M. WALL
TREES ONLY
SITE 5
TESTS 27, 28, & 29
JULY, 1972
RELATIVE ATTENUATION, dBA
RECEIVER DISTANCE FROM WALL, METERS
0
5
10
15
20

Fig. 26

CHAPTER III STATISTICAL ANALYSIS

Experimental data were statistically analyzed under the direction of Dr. Jacob L. Kovner, Principal Biometrician, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, Colorado. The statistical analysis is discussed in a separate chapter for two reasons: we wanted to preserve the perspective of the study from the viewpoint of the statistician, and avoid including statistical terminology with other material in the remainder of the report, where it might confuse the less mathematically oriented reader. Pertinent observations and conclusions have been cross-referenced, however, in Chapter IV, in the interest of completeness.

Automatic data processing (ADP) in the form of analysis of variance and regressions (ANOVA) was applied to the experimental data, to yield equations and their plotted curves.

SITE 1 - HASTINGS: TAPE-RECORDED SOUND

In the ANOVA "A" represents the height of land-fill (land-form), "B" represents the cover (bare form or trees), and "C" represents the distance (measured from the rear edge of the belt). The ANOVA shows, as would be expected, that there are significant differences between the mean sound levels for land-fills of different heights. The analysis also shows that a mean difference of 3.03 dB exists between the bare land-form and tree-covered land-form sound levels. A strong reduction of sound level with distance is also indicated. The interaction AxB was not significant as illustrated in Fig. 27, indicating that the average difference in sound level between bare and tree-covered land-forms is the same at each height level. We note the strong linear effect of height with distance, a somewhat weaker quadratic effect, and no cubic or higher power components.

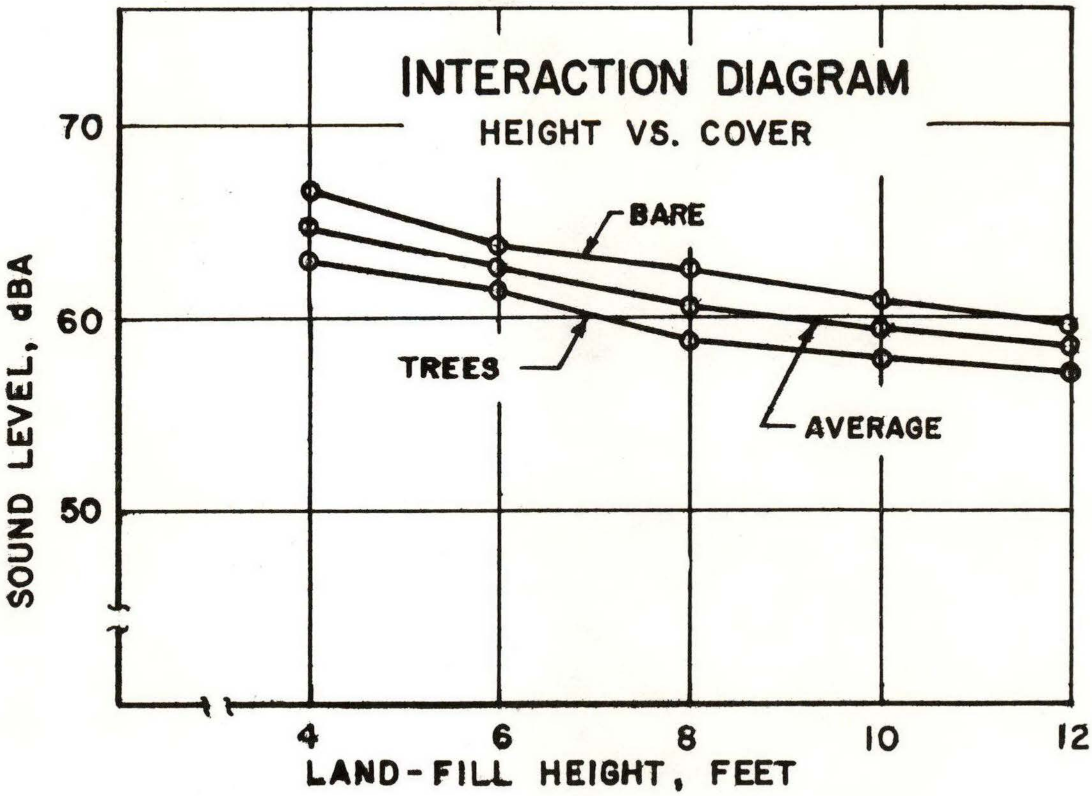

INTERACTION DIAGRAM
HEIGHT VS. COVER
70
60
50
SOUND LEVEL, dBA
BARE
TREES
AVERAGE
4
6
8
10
12
LAND-FILL HEIGHT, FEET

Fig. 27

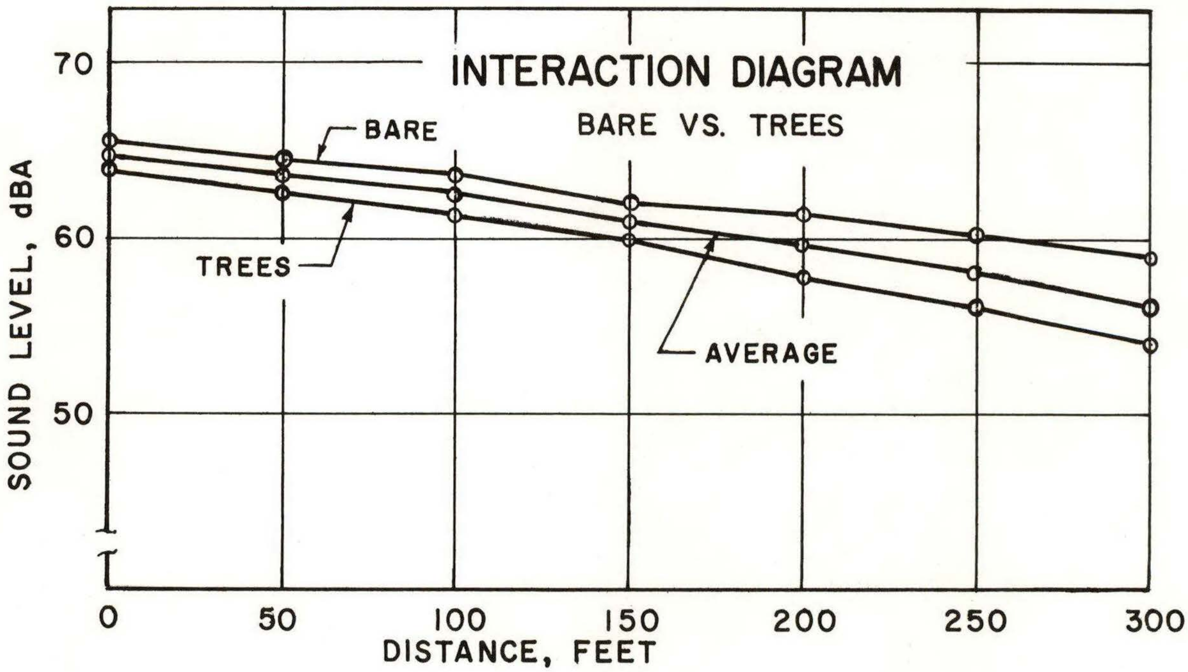

INTERACTION DIAGRAM
BARE VS. TREES
70
60
50
SOUND LEVEL, dBA
BARE
TREES
AVERAGE
0
50
100
150
200
250
300
DISTANCE, FEET

Fig. 28

The interaction BxC (distance x cover) is significant however, as illustrated in Fig. 28, where we note the increasing distance between curves as the source distance increases. Evidently the reduction effect of a tree-covered surface is greater than that of a bare surface, and this effect increases with distance. The interaction of AxC is also significant, (Fig. 29) as indicated by the convergence of lines as we move away from the noise source. Also we note the tendency for the distance between lines at greater heights (8', 10', 12') to be less than at lower heights (4', 6', 8'). Increasing land-fill height above 10 feet results in diminishing returns, indicating a quadratic interaction effect, AC^2. Finally there is an interaction contrast of AxCxB, namely linear height x linear distance x cover. This was determined by the ANOVA to be significant, as indicated in Fig. 30 by the crossing of the set of bare surface curves with the set of tree-covered surface curves -- mainly at distances greater than 125 feet behind the tree belt.

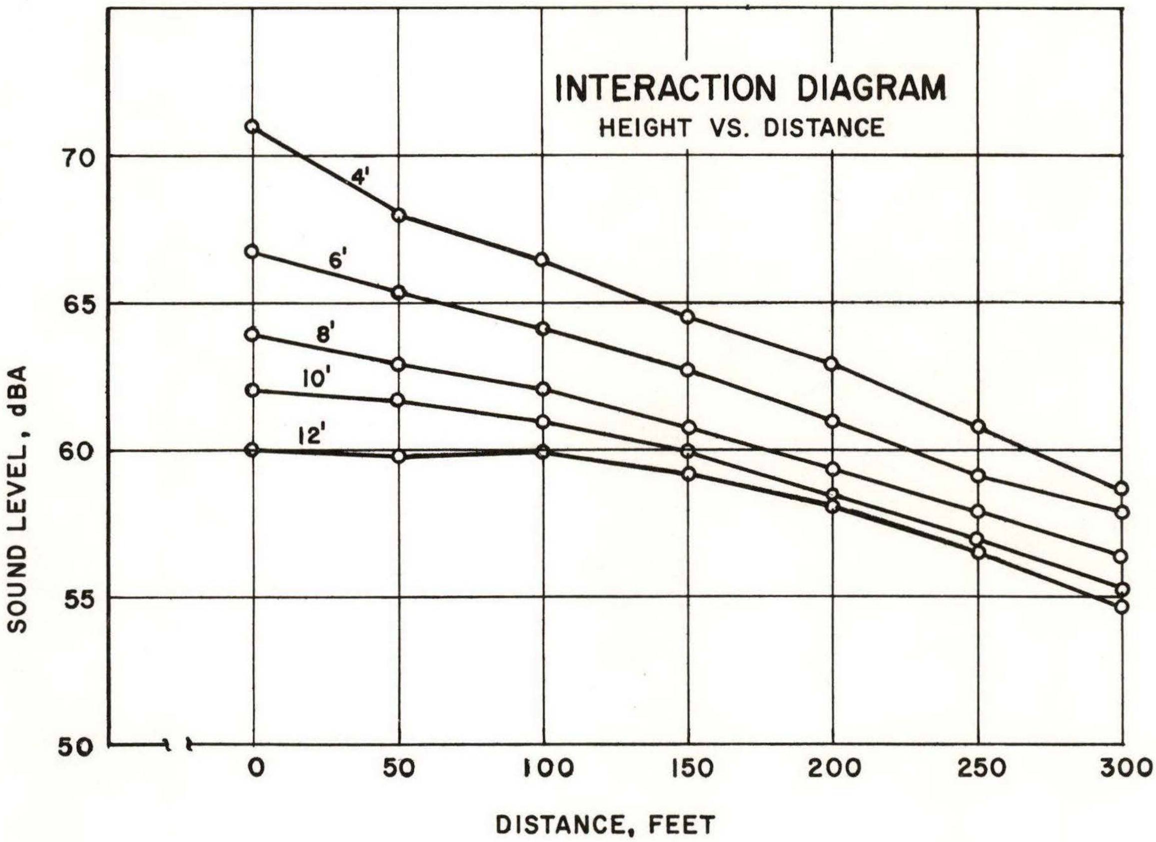
Linear and quadratic equations of sound versus distance for each height of land-fill and for the two cover conditions have been derived. The ANOVA and Fig. 30 indicate that no higher power is required, and that the correlation coefficient for the 2nd degree polynomials is 0.99 or higher. The goodness of fit for the linear regressions suffers for the 10 and 12 foot heights. In arriving at the two model equations, the highly significant linear height x linear distance component has been made use of. The model is $Y = a_o + a_1X_1 + a_2X_2 + a_3X_1X_2$ where

Y = sound level (dBA)

$X_1 = X_D$ = distance (from rear edge of belt to microphone)

$X_2 = X_H$ = height (of land-fill)

A stepwise regression, using dummy variables, has been employed



INTERACTION DIAGRAM
HEIGHT VS. DISTANCE
4'
6'
8'
10'
12'
70
65
60
55
50
SOUND LEVEL, dBA
0
50
100
150
200
250
300
DISTANCE, FEET

Fig. 29

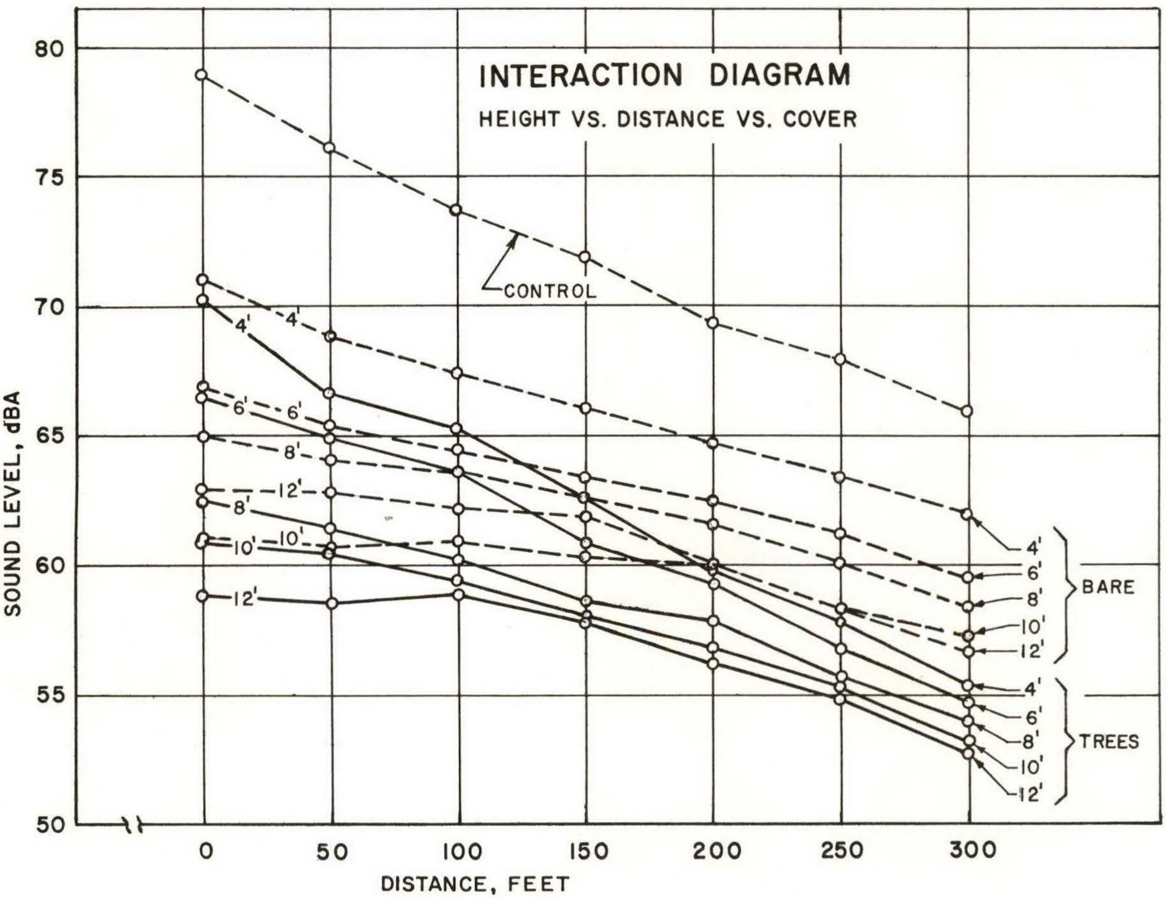

INTERACTION DIAGRAM
HEIGHT VS. DISTANCE VS. COVER
CONTROL
SOUND LEVEL, dBA
DISTANCE, FEET
80
75
70
65
60
55
50
0
50
100
150
200
250
300
4'
6'
8'
10'
12'
BARE
TREES

Fig. 30

to arrive at each set with one pass. We substitute D = 0 and D = 1 to obtain the equations for each set (1), (2).

$$Y_B = 73.933-.035X_D-1.028X_H+.0017X_DX_H \qquad (1)$$

(for the bare land-fill)

and

$$Y_T = 74.334-.061X_D-1.250X_H+.0035X_DX_H \qquad (2)$$

(for the tree-covered land-fill)

A plot of these equations along with observed data points indicated some discrepancy between the observed and fitted values; however, this may be expected from the first approximation. Plots of these equations are not shown, because similar plots, which include a quadratic term are shown later. The results appear to be quite useful, however, and have the advantage of simplicity, with a concise summary of results of the experiments.

The attenuation of sound regressions are obtained by subtracting the above regressions from the control regression, shown in Fig. 3-4, which was determined by the ANOVA to be:

$$Y_C = 78.6607-.0485X_1, \text{ with } r = .99 \qquad (3)$$

We observe again by a trial plot, not shown, a discrepency in the observed and fitted attenuation values, in which the latter ignores the curvature in the former.

Following the previous ANOVA, which ignored the quadratic distance component in the regression of sound level vs. distance, a new analysis was made which included this component. The agreement of fitted to observed data was generally improved, as was to be expected. For first approximations and many practical applications the previous linear analysis may be adequate. However, for land-fills of 12 feet or over the new quadratic analysis is more reliable.

Equations of sound level vs distance which include the quadratic term are:

$$Y_B = 73.933-.0353X_D-1.093X_H+.0033X_DX_H-.0000053X_D^2X_H \tag{4}$$

(for the Bare land-fill)

and

$$Y_T = 74.334-.0606X_D-1.315X_H+.0051X_DX_H-.0000053X_D^2X_H \tag{5}$$

(for the tree-covered land-fill)

These equations and observed points (with connecting lines) are plotted in Figs. 31 and 32. The corresponding attenuation graphs are shown in Fig. 33, although observed curves between 4' and 12' have been omitted to facilitate readability. Attenuation equations, applicable to all heights, are listed, however; these are:

$$\Delta Y_B = 4.728-.0132X_D+1.093X_H-.0033X_DX_H+.0000053X_D^2X_H$$

(for the bare land-fill)

and

$$\Delta Y_T = 4.326+.0121X_D+1.315X_H-.0051X_DX_H+.0000053X_D^2X_H$$

(for the tree-covered land-fill)

A separate analysis to show the comparative effect of high and low wind speed was also made. The seven tests at Site 1 included north winds (in direction of propagation) and south winds (opposing propagation), having speeds of 4, 5, 6, 16, and 17 mph. These were segregated into 2 groups and are subsequently referred to as "low" and "high". The two remaining tests having speeds near zero and 11 mph play a minor role in the analysis. Values for north winds were used primarily for reasons mentioned later.

Sets of equations giving the sound level (dBA) in terms of the distance X_D and land-fill height X_H for "low" and "high" windspeeds

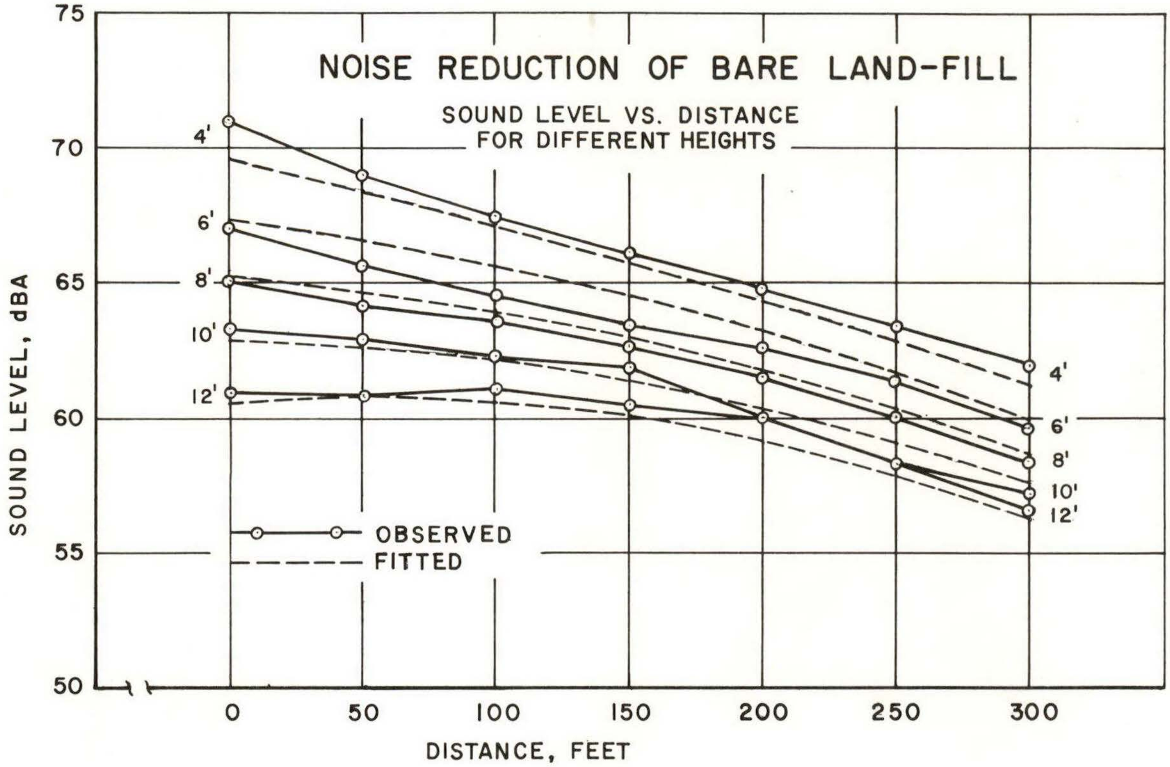

NOISE REDUCTION OF BARE LAND-FILL
SOUND LEVEL VS. DISTANCE
FOR DIFFERENT HEIGHTS
OBSERVED
FITTED
SOUND LEVEL, dBA
DISTANCE, FEET
75
70
65
60
55
50
0
50
100
150
200
250
300
4'
6'
8'
10'
12'

Fig. 31

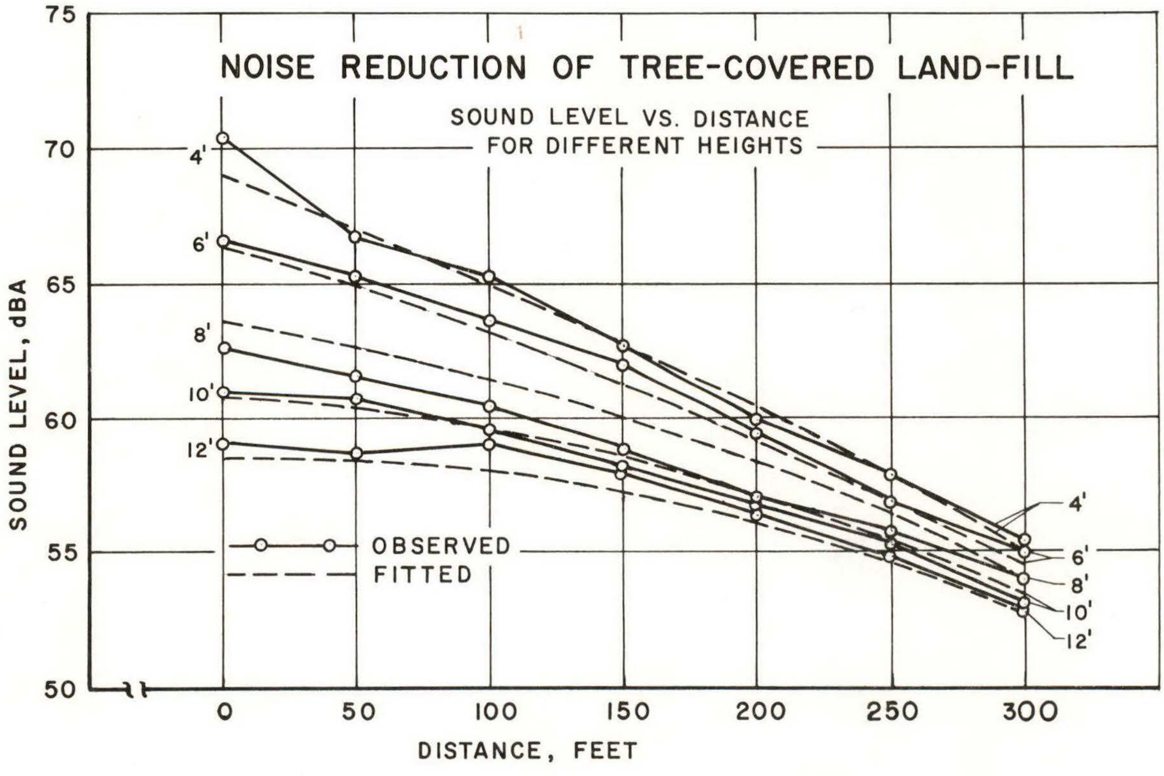

NOISE REDUCTION OF TREE-COVERED LAND-FILL
SOUND LEVEL VS. DISTANCE
FOR DIFFERENT HEIGHTS
OBSERVED
FITTED
SOUND LEVEL, dBA
DISTANCE, FEET
75
70
65
60
55
50
0
50
100
150
200
250
300
4'
6'
8'
10'
12'

Fig. 32

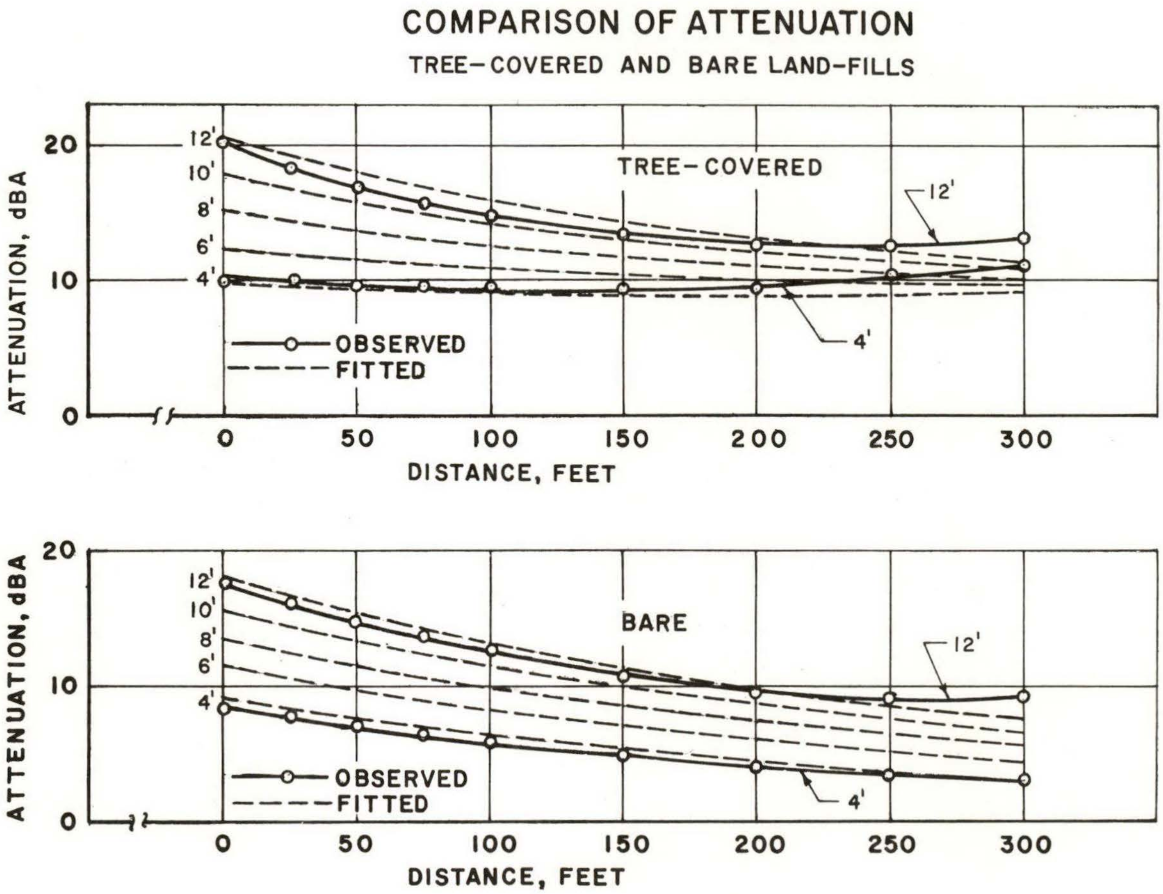

COMPARISON OF ATTENUATION
TREE-COVERED AND BARE LAND-FILLS
TREE-COVERED
ATTENUATION, dBA
20
10
0
12'
10'
8'
6'
4'
OBSERVED
FITTED
0
50
100
150
200
250
300
DISTANCE, FEET
BARE
ATTENUATION, dBA
20
10
0
12'
10'
8'
6'
4'
OBSERVED
FITTED
0
50
100
150
200
250
300
DISTANCE, FEET

Fig. 33

have been derived. The model is:

$$Y = a_o + a_1X_1 + a_2X_2 + a_3X_1X_2 + a_4X_1^2X_2 x10^{-4}$$

where

Y = sound level (dBA)

$X_1 = X_D$ = distance from rear edge of belt to microphone (feet)

$X_2 = X_H$ = land-fill height (feet)

Equations may be formed by reference to tables 1 and 2.

Wind Speed and Direction	Type of Surface	Sound Level dBA	TERMS FOR EQUATION MODEL				
			a_o	a_1X_D	a_2X_H	$a_3X_oX_H$	$a_4X_D^2X_Hx10^{-4}$
North Low	Control	Y_C	79.1143	$-.04914X_D$	----	-----	-----
	Bare	Y_B	73.8350	$-.03090X_D$	$-1.1481X_H$	$+.00398X_DX_H$	$-.08182X_DX_Hx10^{-4}$
	Tree-Covered	Y_T	74.4136	$-.06300X_D$	$-1.3344X_H$	$+.00547X_DX_H$	$-.06341X_DX_Hx10^{-4}$

Table 1 (Low Windspeed)

Wind Speed and Direction	Type of Surface	Sound Level dBA	TERMS FOR EQUATION MODEL				
			a_o	a_1X_D	a_2X_H	$a_3X_oX_H$	$a_4X_D^2X_Hx10^{-4}$
North High	Control	Y_C	78.3571	$-.02771X_D$	----	-----	-----
	Bare	Y_B	75.2715	$-.02674X_D$	$-0.91660X_H$	$+.00330X_DX_H$	$-.04263X_DX_Hx10^{-4}$
	Tree-Covered	Y_T	75.5343	$-.04217X_D$	$-1.24865X_H$	$+.00419X_DX_H$	$-.04263X_DX_Hx10^{-4}$

Table 2 (High Windspeed)

Graphs of the equations are illustrated in Figs. 34 and 35.

We now subtract the bare and tree-covered land-fill regression values from the control values to obtain the following table of attenuations (Table 3). North wind (down-wind sound propagation) only has

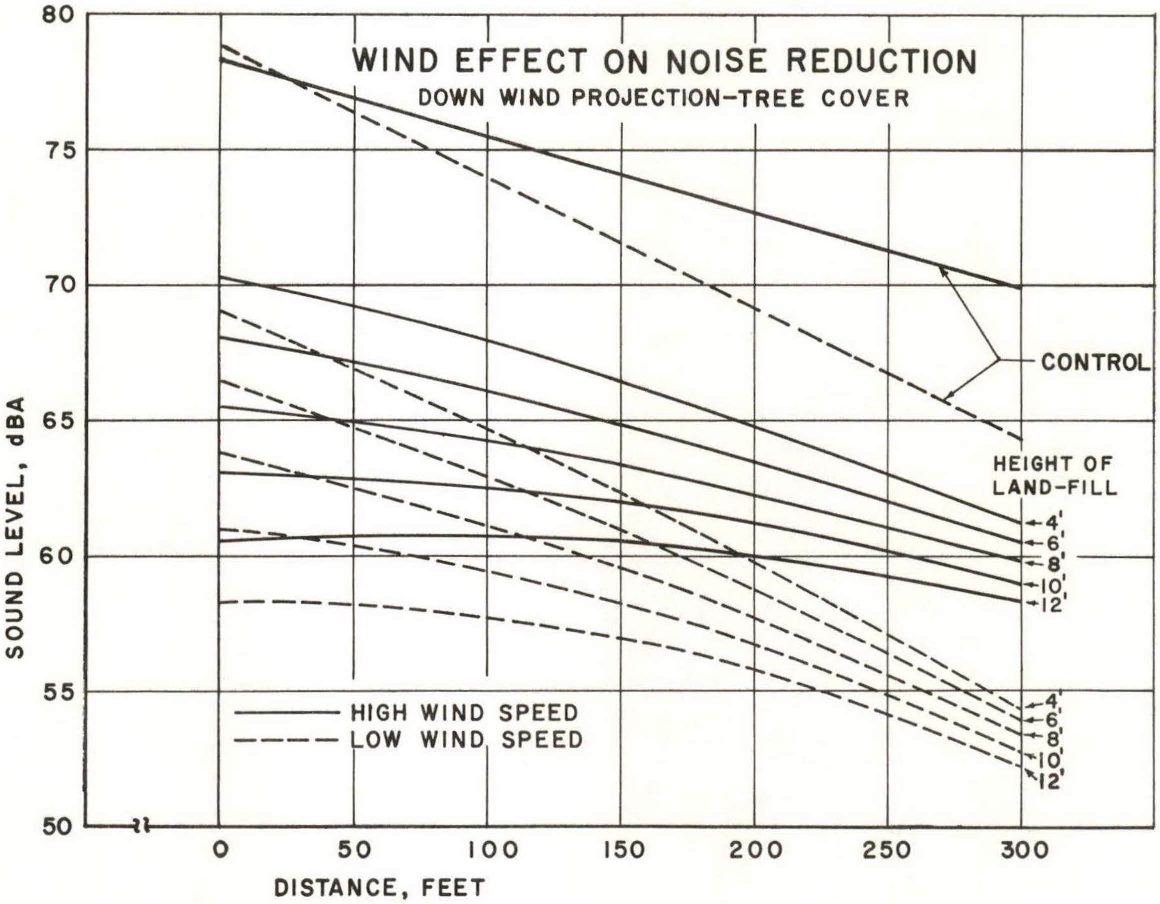
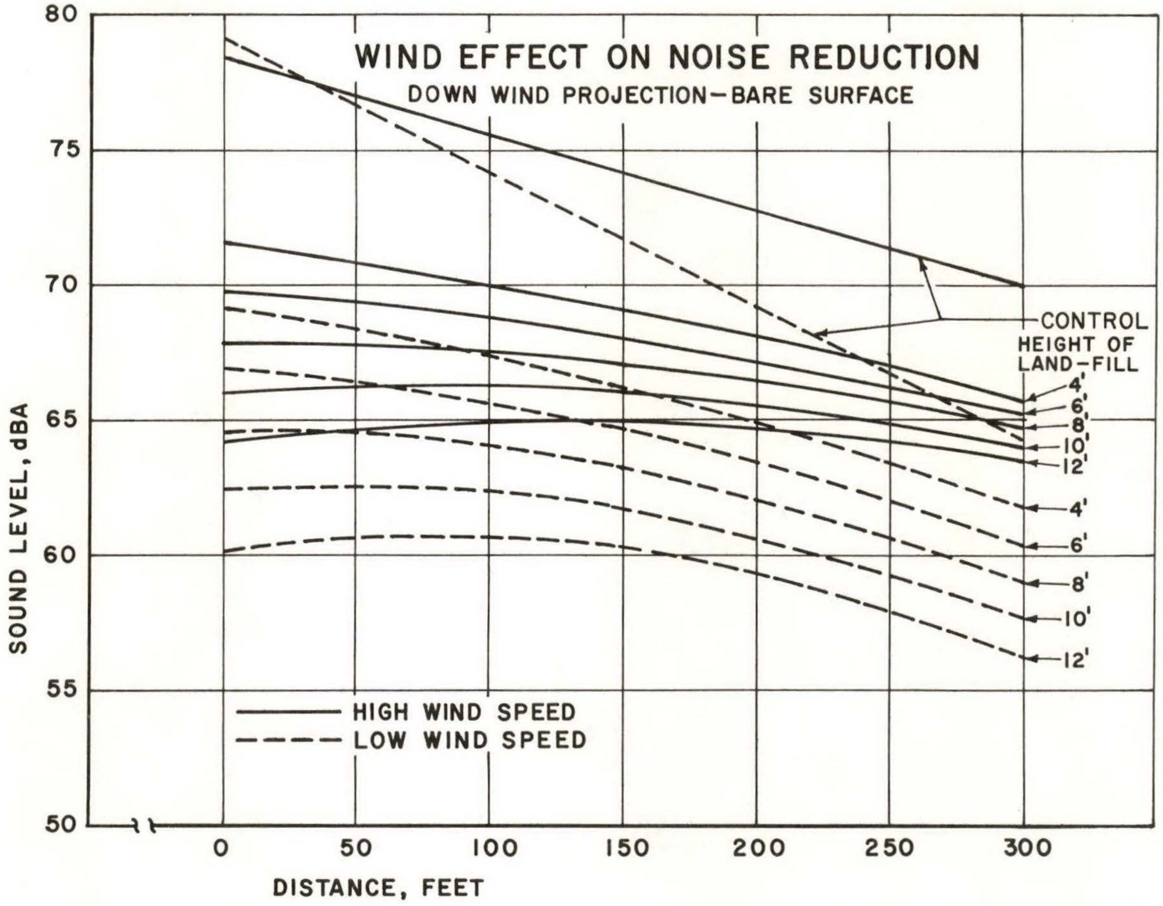

WIND EFFECT ON NOISE REDUCTION
DOWN WIND PROJECTION-TREE COVER
SOUND LEVEL, dBA
80
75
70
65
60
55
50
DISTANCE, FEET
0
50
100
150
200
250
300
CONTROL
HEIGHT OF LAND-FILL
4'
6'
8'
10'
12'
4'
6'
8'
10'
12'
HIGH WIND SPEED
LOW WIND SPEED

Fig. 34



WIND EFFECT ON NOISE REDUCTION
DOWN WIND PROJECTION—BARE SURFACE
CONTROL
HEIGHT OF LAND-FILL
4'
6'
8'
10'
12'
4'
6'
8'
10'
12'
HIGH WIND SPEED
LOW WIND SPEED
SOUND LEVEL, dBA
80
75
70
65
60
55
50
0
50
100
150
200
250
300
DISTANCE, FEET

Fig. 35

been included, since north wind attenuation values were found to be close to south wind values.

North Wind Speed	Type of Surface	Attenuation dBA	TERMS OF EQUATION MODEL				
			a_o	a_1X_D	a_2X_H	$a_3X_DX_H$	$a_4X_D^2X_H x10^{-4}$
Low	Bare	Y_B	5.3	$-.0182X_D$	$+1.148X_H$	$-.00398X_DX_H$	$+.082X_D^2X_H x10^{-4}$
	Tree-Covered	Y_T	4.7	$+.0139X_D$	$+1.334X_H$	$-.00547X_DX_H$	$+.063X_D^2X_H x10^{-4}$
High	Bare	Y_B	3.1	$-.0010X_D$	$+0.917X_H$	$-.00330X_DX_H$	$+.043X_D^2X_H x10^{-4}$
	Tree-Covered	Y_T	2.8	$+.0145X_D$	$+1.249X_H$	$-.00419X_DX_H$	$+.043X_D^2X_H x10^{-4}$

Table 3 (Attenuations)

Graphs of the attenuation are illustrated in Figs. 36 and 37.

Finally we show equations for the difference between high and low wind speeds in Table 4 as follows:

Type of Surface	Difference of Attenuation dBA	TERMS OF EQUATION MODEL				
		a_o	a_1X_D	a_2X_H	$a_3X_DX_H$	$a_4X_D^2X_H x10^{-4}$
Bare	Y_B	2.2	$-.0172X_D$	$+.231X_H$	$-.00068X_DX_H$	$+.039X_D^2X_H x10^{-4}$
Tree-Covered	Y_T	1.9	$-.0006X_D$	$+.086X_H$	$-.00128X_DX_H$	$+.021X_D^2X_H x10^{-4}$

Table 4 (Attenuation Differences)

These differences are also illustrated graphically in Fig. 38.

A set of curves for a south wind (up-wind sound propagation) is also shown (Fig. 39) to illustrate the rapid decrease of sound level with distance. Equations for this case are not included, however, since the

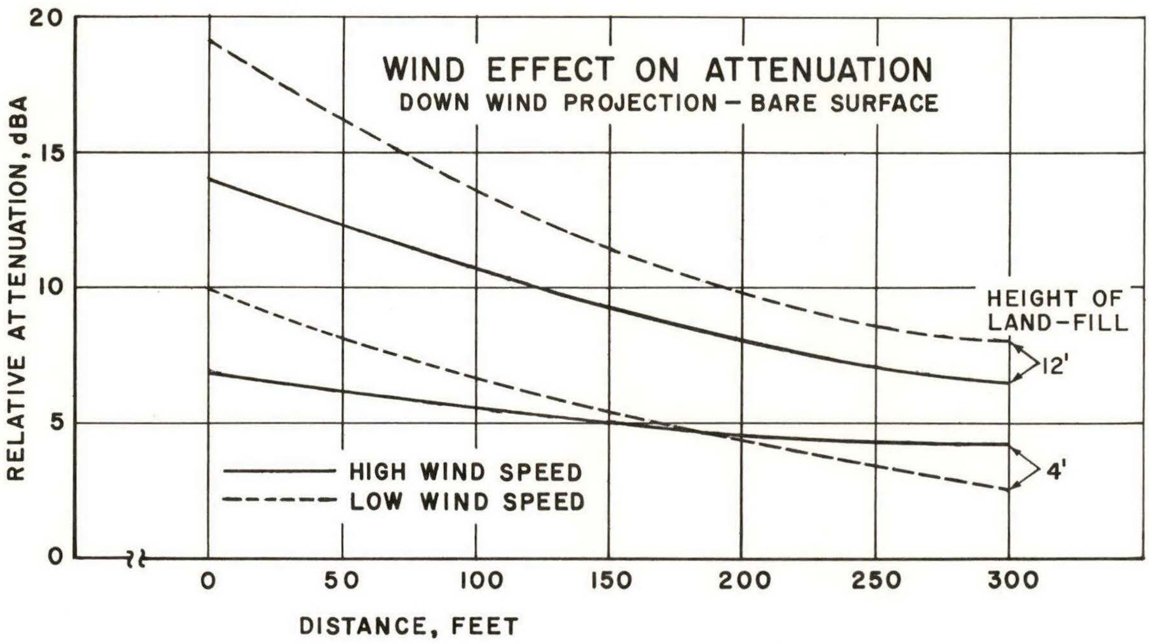

WIND EFFECT ON ATTENUATION
DOWN WIND PROJECTION – BARE SURFACE
RELATIVE ATTENUATION, dBA
0
5
10
15
20
DISTANCE, FEET
0
50
100
150
200
250
300
HIGH WIND SPEED
LOW WIND SPEED
HEIGHT OF LAND-FILL
12'
4'

Fig. 36

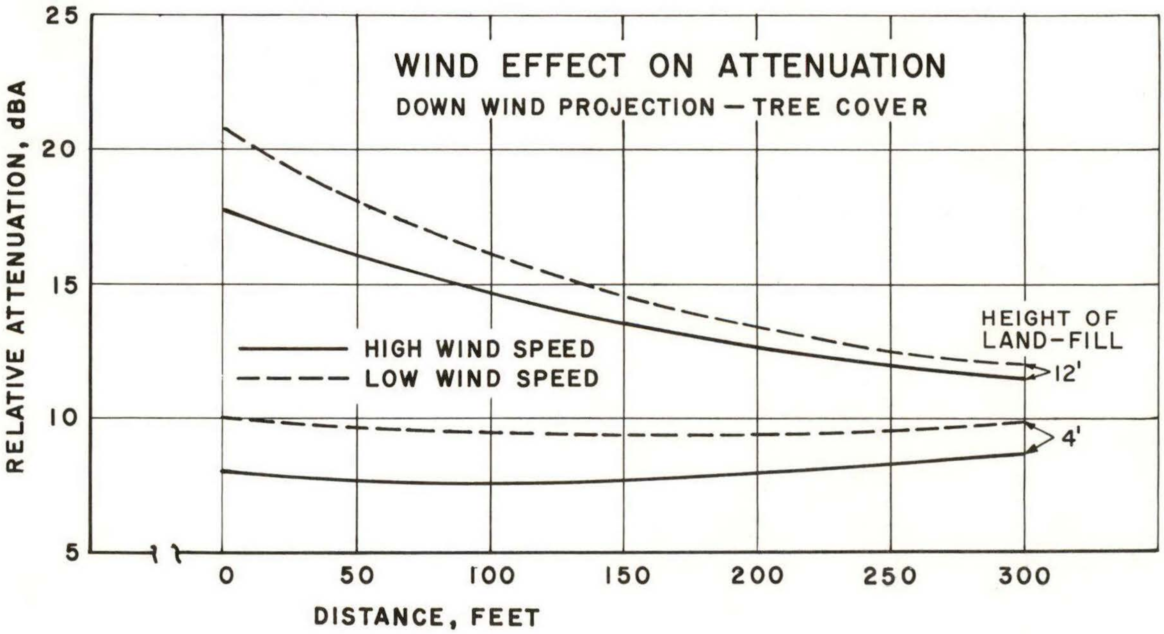

WIND EFFECT ON ATTENUATION
DOWN WIND PROJECTION – TREE COVER
RELATIVE ATTENUATION, dBA
5
10
15
20
25
DISTANCE, FEET
0
50
100
150
200
250
300
HIGH WIND SPEED
LOW WIND SPEED
HEIGHT OF LAND-FILL
12'
4'

Fig. 37

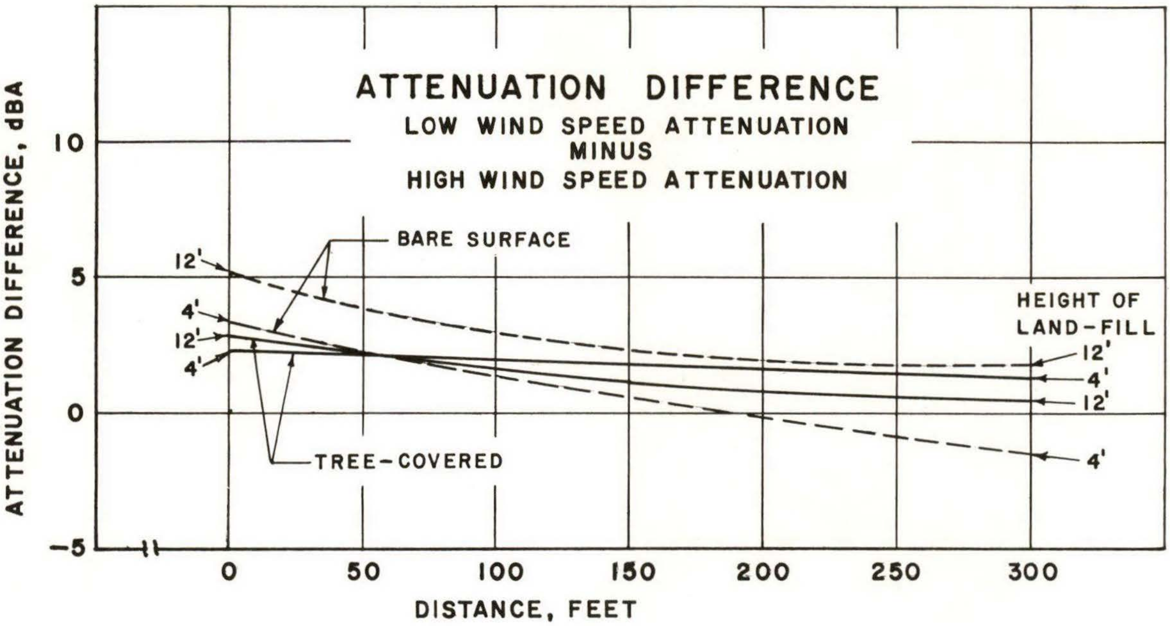

ATTENUATION DIFFERENCE
LOW WIND SPEED ATTENUATION
MINUS
HIGH WIND SPEED ATTENUATION
ATTENUATION DIFFERENCE, dBA
10
5
0
-5
BARE SURFACE
TREE-COVERED
12'
4'
12'
4'
HEIGHT OF
LAND-FILL
12'
4'
12'
4'
0
50
100
150
200
250
300
DISTANCE, FEET

Fig. 38

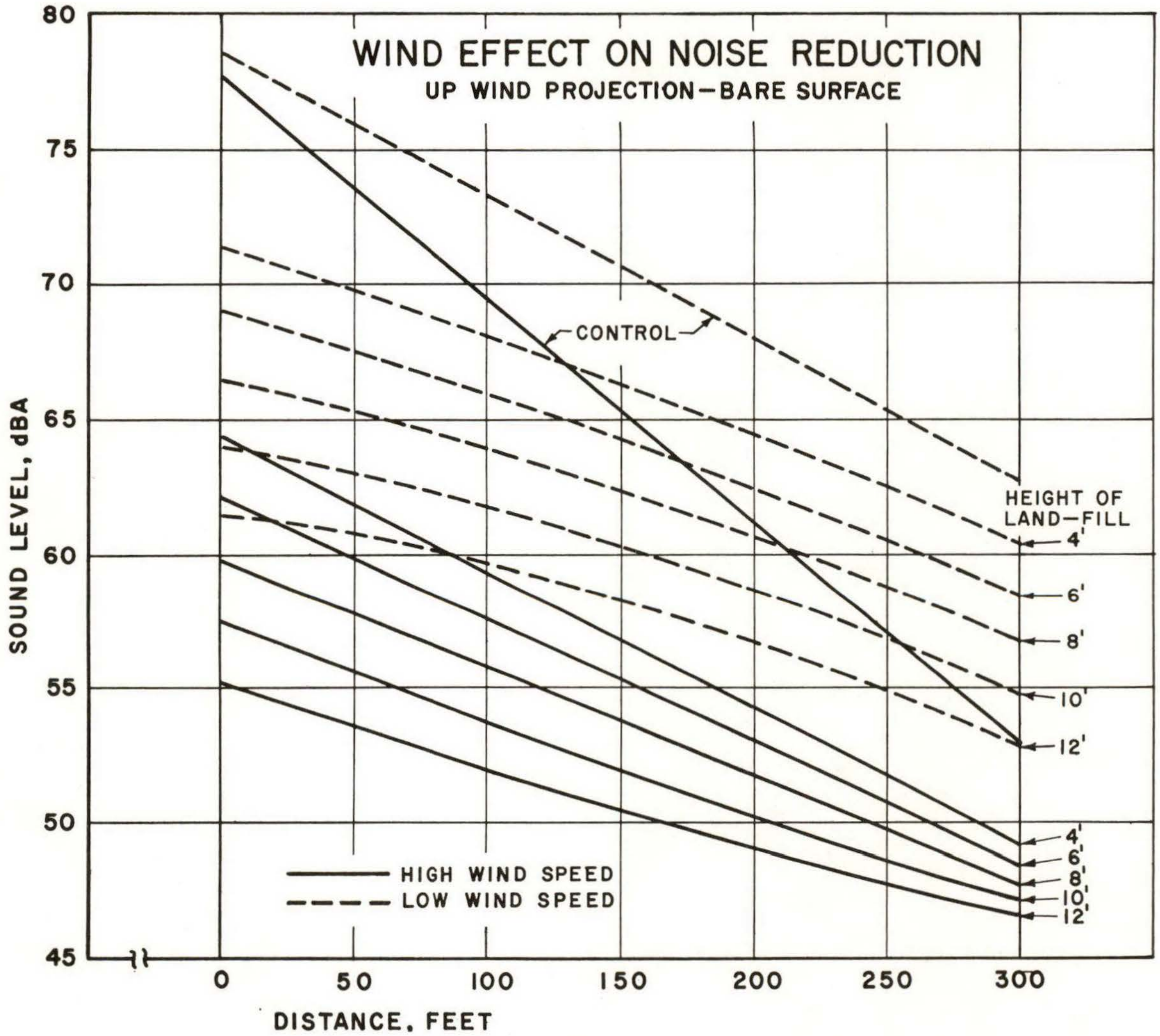

WIND EFFECT ON NOISE REDUCTION
UP WIND PROJECTION-BARE SURFACE
SOUND LEVEL, dBA
80
75
70
65
60
55
50
45
CONTROL
HEIGHT OF
LAND-FILL
4'
6'
8'
10'
12'
4'
6'
8'
10'
12'
HIGH WIND SPEED
LOW WIND SPEED
0
50
100
150
200
250
300
DISTANCE, FEET

Fig. 39

more severe down-wind case usually governs in a practical design situation.

The following conclusions may be drawn by reference to Figures 34 to 39: From figs. 34 and 35 comparison of the high and low wind speed curves show, as expected, that a higher noise level is maintained, at a given distance, with the higher wind speed. Fig. 39, an up-wind projection, shows the opposite effect. When we compare the control test sound levels at 300 feet for the low down-wind (Fig. 34) and low up-wind (Fig. 39) projections we note only a 2 dB difference, whereas if we compare the corresponding high wind speed projections we note a 17 dB difference. Evidently the sound is carried along more with the higher winds, and low wind speeds do not greatly affect the sound propagation.

Figures 36 and 37 indicate that the attenuation effect of the treatments (bare or tree-covered) is not greatly affected by wind speed. In general, there is a decreasing attenuation as wind speed increases, but the decrease is less at greater distances. Fig. 38 shows this effect, and we note that the range of attenuation differences is less than 5 dB.

SITES 2 and 3 - MILFORD HIGHWAY CUTS AND FILLS

These sites are of similar tree structure and ground configuration; they represent rather typical situations where a major highway passes through rolling hills. We have made certain comparisons of their acoustical characteristics with those of (Hastings) the principal test site. The first comparison is made of site 3 with site 1, using tests from both sites which have similar wind conditions, i.e. fairly high wind in the direction of sound propagation. The following equations, derived from the analysis, give the sound level in dBA units:

SITE 1

TREE $Y_T = 73.8914-.0467X_D-1.0900X_H+.00250X_DX_H$

CONTROL $Y_C = 78.7357-.0384X_D$

ATTENUATION $\Delta Y = 4.8443+.0083X_D+1.0900X_H-.00250X_DX_H$

SITE 3

TREE $Y_T = 72.7428-.0436X_D-1.1516X_H+.00131X_DX_H$

CONTROL $Y_C = 77.8750-.0359X_D$

ATTENUATION $\Delta Y = 5.1322+.0077X_D+1.1516X_H-.00131X_DX_H$

The attenuation equations for the above sites are essentially the same; this might be expected, since the land-form height, tree height and belt width were comparable. Ground configurations are not identical, however, and the similarity should be viewed with some caution, when making comparisons.

SITE 2, was unique in that it contained both a cut (depressed highway) and a fill (elevated highway). We made a comparison of the cut and fill through the analysis. The winds were all in the direction of sound propagation and ranged from 3 to 15 mph - a rather good coverage of usual conditions. Results of the analysis are shown graphically in Fig. 40; where curves of sound level (dBA) versus distance, attenuation versus distance have been plotted. An average attenuation curve for fills is shown, rather than 4 separate curves, in the interest of readability. Less than 2 dB from the mean attenuation at each distance is noted, and the curves overlap, for no apparent reason. We observe the progressive effect from cut to fill, and a rather abrupt change from the

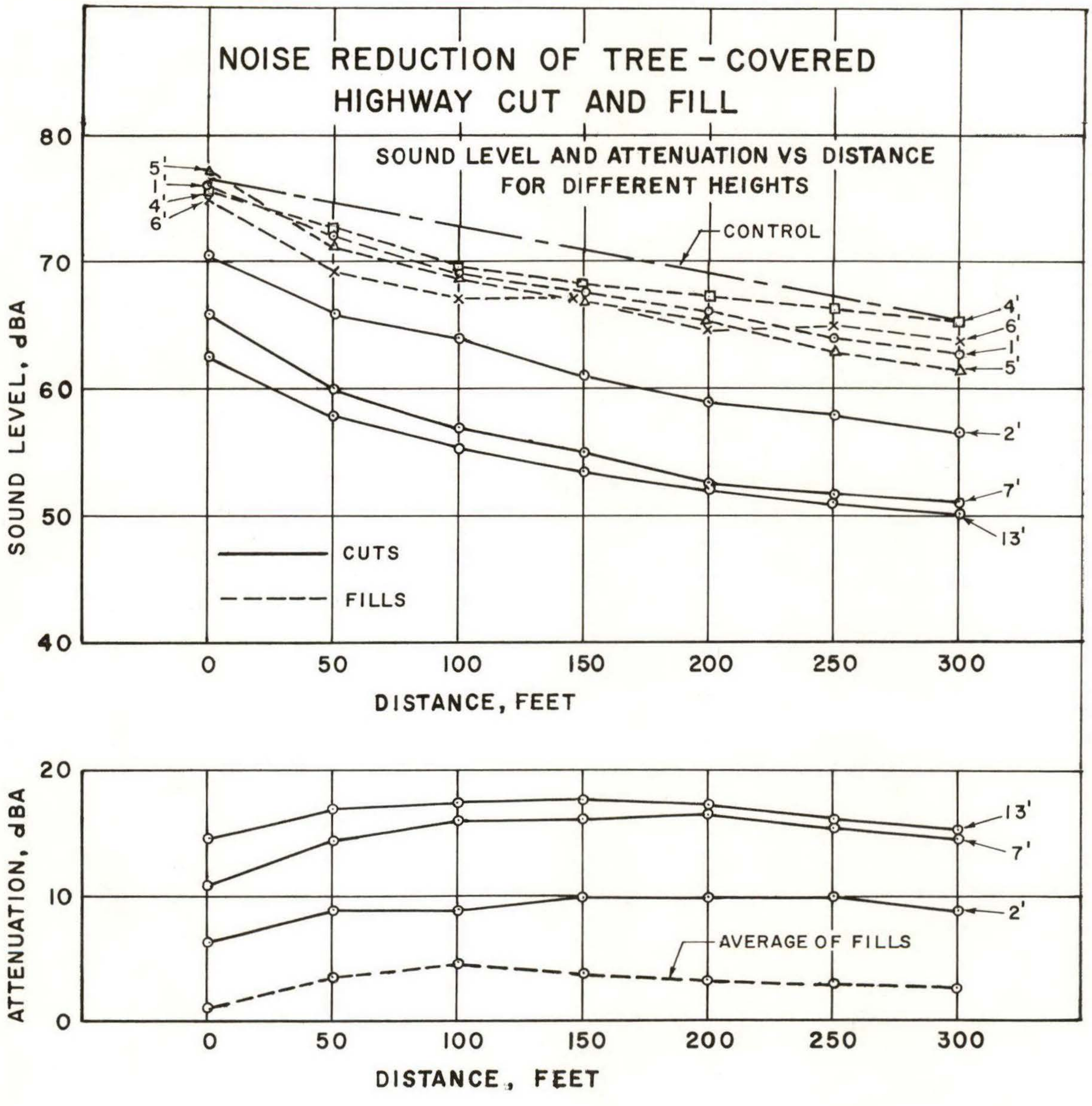

NOISE REDUCTION OF TREE - COVERED HIGHWAY CUT AND FILL
SOUND LEVEL AND ATTENUATION VS DISTANCE FOR DIFFERENT HEIGHTS
CONTROL
CUTS
FILLS
SOUND LEVEL, dBA
DISTANCE, FEET
ATTENUATION, dBA
AVERAGE OF FILLS
DISTANCE, FEET
5'
1'
4'
6'
2'
7'
13'
80
70
60
50
40
20
10
0
0
50
100
150
200
250
300

Fig. 40

+2 foot to -1 foot elevation, due perhaps to the ground configuration blocking out a portion of the direct sound coming from the source. The lower (attenuation) curves indicate the greater reduction of the deeper cuts and the relatively low attenuation of the fills, which suggest the undesirable acoustical properties of an elevated highway.

SITE 5 - PLATTSMOUTH TREE-WALL SCREEN

Tests at this site extend over a relatively short period of time, and the results should, therefore, be considered tentative. The data appears to be quite consistent, however, and the gross effects are believed to be reliable.

The data from this site have been analyzed as a factorial. Surface treatments (trees only, bare wall, trees and wall) are denoted "T". Source distance is denoted "SD" and microphone distance "MD". Each factor is at 4 levels. The treatments (T) are also factorial, and may be used to estimate tree, wall, and interaction main effect. A check of the data indicates that although there are three different wall heights at each date these may be ignored, and the dates treated as replications.

Interaction diagrams of the variables (TxSD) and (TxMD) are shown in Figs. 41 and 42 respectively. From the interaction diagram in Fig. 41 we note that the average attenuation tends to decrease, shown by the converging lines, as the source is moved away from the wall. The source effect appears to be mainly linear, despite a reversal at 10 to 15 meters. Also the average sound level decreases as the source is moved farther away from the wall, and the total transmission distance increases - this is to be expected.

From the interaction diagram Fig. 42, we note a characteristic decrease

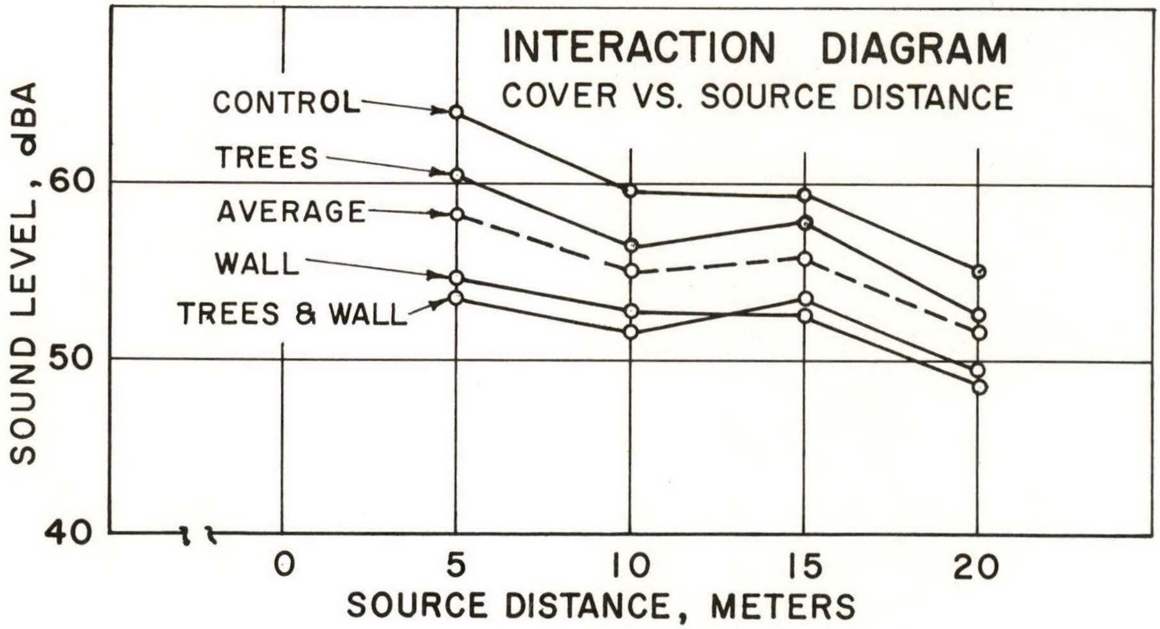

INTERACTION DIAGRAM
COVER VS. SOURCE DISTANCE
CONTROL
TREES
AVERAGE
WALL
TREES & WALL
SOUND LEVEL, dBA
60
50
40
0
5
10
15
20
SOURCE DISTANCE, METERS

Fig. 41

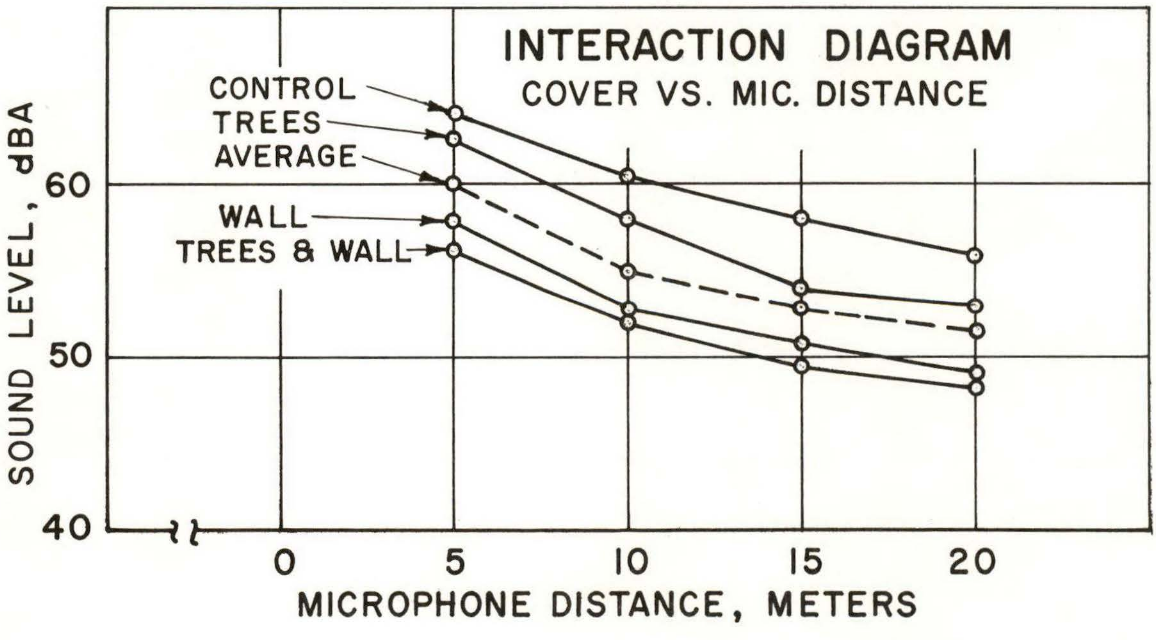

INTERACTION DIAGRAM
COVER VS. MIC. DISTANCE
CONTROL
TREES
AVERAGE
WALL
TREES & WALL
SOUND LEVEL, dBA
60
50
40
0
5
10
15
20
MICROPHONE DISTANCE, METERS

Fig. 42

of sound level with distance, and no significant variation in attenuation over the limited 20 meter distance. The three way interaction diagram yielded no significant effects and is not shown.

We conclude from the analysis that the treatment effect is highly significant, and is mainly due to the wall effect, whereas the tree effect is not very evident. The former shows an average attenuation of 7.5 dBA (for wall alone) compared with 2.8 dBA (for trees alone). The wall and tree combination behaves much like trees alone, due perhaps to the relatively low tree height at this test site.

Attenuation regressions have been derived and are given by

WALL $Y_W = 13.0450-.3610X_S-.1340X_M+.0035X_SX_M$

TREES AND WALL $Y_{T+W} = 10.1000-.2730X_S-.0220X_M+.0072X_XX_M$

TREES $Y_T = 2.055-.0510X_S-.1300X_M-.0016X_SX_M$

where X_S equals the source distance and X_M equals the microphone distance. We note that the attenuation is reduced about 1.5 dBA for each 5m increase in source distance over the 20m range. Experimental curves of sound level vs distance and attenuation vs distance have been shown in Chapter II, and are not calculated from the statistical analysis.

Conclusions from the statistical analysis have also been included in Chapter IV, along with general conclusions of the study.

CHAPTER IV OBSERVATIONS AND CONCLUSIONS

Observations and conclusions resulting from the statistical analysis and from the observed results are both included; further details from the statistical analysis are found in Chapter III.

SITE 1 - HASTINGS LAND-FORM

Observing the experimental results, we conclude that this tree belt, by itself, offered only medium noise protection. Attenuations (reduction in sound level) in the 4 to 6 decibel range were measured, whereas earlier tests of other belts indicated 5 to 8 dBA reduction as typical. This was attributed to the medium height of the trees (about 25 feet) and to the large number of dead trees in the center rows. Addition of the land-form within the belt materially increased its noise-reducing property, expecially in the area immediately behind the belt.

The average sound level difference in bare and tree-covered land-forms for all readings, as determined by the statistical analysis, was only slightly over 3 decibels. Evidently the higher land-forms take the place of the first several feet of tree height, for close-to-belt positions, and the trees tend to become more effective at lower land-form heights and at greater distances behind the structure.

Fig. 3, which represents an average of all tests run in 1971 and 1972, using tape-recorded truck noise as a source, shows sound levels well below 68 dBA for the entire area behind the belt, and this holds for all heights of land-forms tested. The 68 dBA level has been found by personal interview studies (7) to be the dividing point between "disturbing" and "not disturbing" for daytime out-of-door activities. Conversational speech interference seldom occurs below this level. The

more desirable level, according to many experimenters, of 60 dBA is also observed at distances exceeding 300 feet from the noise source, provided the higher (8') land-form and tree combination is used. Although 60 dBA is normally considered too noisy for evening hours, it is very acceptable for daytime outdoor environments, and corresponds to indoor levels found in a larger office or store.

The attenuation, observed from the lower curves, indicates reductions greater than 10 dBA (approximately half as loud) for most locations. This reduction is based on a comparison of the same sound projected over the level control surface, which is devoid of trees and land-form, but otherwise similar. The reduction of sound is thus attributable to the trees and land-form and not to other factors, such as distance, atmospheric absorption, etc.

The sound levels shown on the graphs are undoubtedly higher than those which would be encountered in most actual situations, because the projected level of the tape-recorded sound was set for the noisiest of highway trucks. Also dissimilarities between the tape-recorded point source projection and an actual noise emitted from a passing truck appear to enter the picture. We may observe the difference in sound levels by comparing the tape-recorded sound graphs (Figs. 3, 4, and 5) with the actual (live) sound graphs (Fig. 8) and noting that the actual sound levels are from 4 to 10 dBA below the tape-recorded levels. The use of tape-recorded sound, however, provided better control, greater precision, and a tremendous saving in the time required to obtain a significant number of readings.

It is likely that the curves of Fig. 3, if used for design purposes, would give estimates of sound levels 4 to 8 decibels higher than would

actually be encountered, and are thus on the "conservative" side. The curves of Figs. 3 to 6 could be used to predict the sound levels which would be encountered in an area adjacent to a major highway where similar tree and land-form protective devices were installed.

Figure 4 for bare land-forms parallels Fig. 3 for the tree-land-form combination. It also shows the sound levels which could be expected behind land-forms of varying height, as well as the attenuation attributable to the presence of the barrier. For design purposes these levels could represent initial conditions of a developing plan for noise screening, where trees of such small size were planted that their initial noise screening effect would be negligible. Both Figs. 3 and 4 are therefore useful in a long-term plan.

SITES 2 and 3 - MILFORD HIGHWAY CUTS

Observing the experimental results (Figs. 16 and 19) we conclude that a combination of a depressed highway and a tree belt offers a very effective means for reducing traffic noise. Test results from the two sites are quite comparable, and reductions in the 10 to 18 dBA range are noted for cuts from 2 to 13 feet deep when combined with 100-foot-wide tree belts. When the cut changes to a fill, however, we observe relatively low attenuation -- less than 5 dBA -- and conclude that some of the noise screening ability of the trees is lost when the highway is elevated. Probable reasons for the loss are the relative reduction in tree height and the projection of a larger part of the wave front toward the upper less dense portion of the tree structure.

When we compare the noise reducing properties of sites 2 and 3 (highway cuts) with those of site 1 (raised land-form) we observe the highway cuts are more efficient at greater distances. A contributing

factor which may account for this difference is the total height of the combination of trees and land-form. At sites 2 and 3 the height of the trees -- located atop the highway cut -- is added to the depth of cut, whereas at site 1, the trees start at the base of the land-form, and the portion of the branches and leaves above the land-form is considerably smaller. Another factor is the ground configuration differences at the two sites, which may affect the wind gradient and thereby the sound propagation characteristics. Whatever the reasons for the difference, we must not overlook the importance of structure height in efficient noise screening.

SITE 4 - GRETNA REST AREA

This site, which was lacking in significant tree cover, was used mainly for comparison with other tree-covered sites. We do conclude, however, from the experimental results (Figs. 21 and 22) that a natural hill may offer some protection from traffic noise, even though the tree cover is minimal. Attenuations in the order of 8 to 10 dBA were observed behind the hill -- a reduction in observed loudness of about half.

When we compare the 8 to 10 dBA attenuations of the 20-foot-high hill of site 4 with the 18 to 20 dBA attenuations of the 12-foot-deep tree-topped highway cuts of sites 2 and 3, we conclude that the effect of the trees was indeed appreciable, and that the addition of substantial numbers of trees to a relatively barren hill would extend the range of noise protection.

SITE 5 - HORNING STATE FARM AT PLATTSMOUTH

Observations and conclusions from the test results at this site are based on fewer numbers of tests conducted over a shorter period of time

than at the other four sites. We therefore consider them somewhat tentative, although several significant effects appear to be well established.

The relative noise screening effects of grass surface, trees alone, wall alone and tree-and-wall combination are compared in Fig. 24. We observe that the trees are more efficient than the grass surface, and that the wall is more efficient than the trees; also that the trees and wall offer the most efficient combination, although only slightly more so than is the wall itself. An explanation for this is that the wall replaces the most effective part of the tree, which is near the ground where the structure is most dense, and a considerable part of the sound passes between the trees near their upper part. We recall that the trees are relatively young and only 2 to 3 times the wall height at their tops, and would expect to see improvement of the trees relative to the wall as the trees matured.

The placement of the combined tree-wall structure also affects its noise reducing properties as illustrated in Fig. 25. We observe attenuations in the 10 to 13 dBA range when the structure is close to the noise source, whereas this drops off to the 7 to 9 range when the structure is further away. Similar effects had been noted in the earlier study (11). We conclude that a noise screen of this type should be placed relatively close to a noise source for most efficient application.

Wall height effect on noise reduction is observed in Fig. 26. We note that low walls offer no more protection than does the relatively young tree belt by itself, but that the combination of higher walls, above 1.4 meters, with trees does provide considerable protection.

We conclude that if only slight noise protection is needed, a few rows of trees will serve as well as a low wall. Where the situation is more severe, however, a higher wall is deemed necessary, especially when the trees are young. When the trees are more mature the wall might be removed or replaced by dense bushes, with little sacrifice of noise protection in many instances.

TREE-COVER EFFECT

Perhaps the most significant characteristic of this effect is illustrated by the noise reduction and attenuation curves of Figs. 3 and 4. The greater attenuation provided by the tree-covered land-form at distances over 300 feet from the noise source compared to that of the bare land-form is appreciable. The trees apparently tend to extend the range of noise protection as well as to add directly to that offered by the land-form alone. This fact is further supported by the statistical analysis, and is illustrated in Figs. 28 and 33.

At closer distances the reduction attributed to trees is less than at greater distances. Explanation for this, we believe, is related to different wind gradients created by the bare and tree-covered land-form. In the case of the bare land-form, the wind was observed to be low immediately behind the barrier, but to reach its original speed in about 100 feet, whereas for the tree-covered land-form, the low wind speed was maintained for over 200 feet. The more porous tree-cover and added height may have accounted for this phenomenon. Also, the shape of the advancing wave front may be altered in a different way by a bare land-form than by a tree-covered land-form. Diffusion of the front before it reaches the land-form is probably different for bare and tree-covered surfaces, especially if several rows of trees are located between the

noise source and the form. Regardless of the reasons, both the observed results and the statistical analysis point to this very significant effect.

LAND-FORM HEIGHT EFFECT

The amount of noise reduction due to different heights of land-forms is shown by the graphs of Fig. 33 from the statistical analysis. The increase in attenuation with land-form height is generally recognized. Therefore test results are of interest mainly for their actual numerical values. Also, the interaction of height and tree-cover are of special interest. There appear to be options in the means for obtaining a prescribed amount of noise reduction. For example, we might wish to provide a relatively high land-form with a minimum tree cover, or provide a lower land-form and increase the amount of plantings. Either alternative could yield similar attenuation, and other considerations of cost, aesthetics, etc. might be determining factors.

WIND EFFECT

Wind, often omitted from consideration in plans for outdoor noise control, plays a major role in the propagation of sound. Statistical analysis indicates that sound levels may differ by 17 dB at a 300-foot-distance depending on wind speed and whether the wind opposes or favors the sound propagation (Figs. 35 and 39). This variation corresponds, approximately, to a factor of 3 in apparent loudness. The relative attenuation, however, changes relatively little due to variations of wind direction and magnitude. Evidently the amount of attenuation (decibel reduction) afforded by a noise screen of this type is nearly independent of wind (Fig. 37); the actual noise level will of course

vary as the wind changes.

Earlier studies with wide belts of tall dense trees have indicated that tree-type noise screens are most effective in a down-wind sound projection, which is the more severe condition.

Low wind speeds, under 8 miles per hour, do not materially affect sound propagation, but since average wind speeds in many parts of the country are in the 10-15 mph range, it would seem advisable to consider this effect in noise control designs.

TREES VS LAND-FORM CONSIDERATIONS

We have seen that both trees alone and land-forms alone have demonstrated ability to reduce intrusive noise. Also the present study indicates a combination of the two is more effective than either one, when used separately. The considerations for a choice between the alternatives are many, and a full discussion of them is beyond the intent of this study. However, we do wish to point out some of the more important ones, lest they be overlooked in a proposed design for noise control.

Cost and availability of materials is often a primary consideration. The cost of large numbers of trees must be balanced against the cost of moving large quantities of earth. In areas where trees are readily available but earth is at a premium, the emphasis on tree usage is indicated, whereas an existing hill may, with slight modification, provide a "ready made" land-form, which would then be the primary means for noise control.

Urgency of the situation may also be a factor. Land-forms can be constructed almost overnight, whereas several years may be required to develop a tree structure which is capable of providing substantial noise

protection. In a long range plan, however, the lack of urgency may indicate extensive use of plant materials, especially if these are to serve other purposes than simply providing noise protection.

Aethetics may also be of major consideration. Some neighborhoods would not tolerate a large bare mound of earth, but would respect a terraced structure having rows of plantings which eventually would provide a softer profile, and increasing noise protection as the trees matured. Perhaps the most judicious choice in the majority of cases would be some combination of trees and land-forms or other solid barriers. This should be determined from a consideration of all pertinent factors by landscape architects, highway design engineers and community planners.

LIMITATIONS AND REQUIREMENTS OF OUTDOOR NOISE CONTROL

Complete control of sound requires full enclosure of the noise source; the "open" nature of the outdoors therefore dictates to some extent the amount of control possible. Some sound will travel over the top of any barrier of reasonable height, and around its sides. The wind, or more probably the wind gradient, tends to "carry" the sound over obstacles in the direction of its motion, and to increase the sound level down-wind over what would normally be expected with no wind present.

Temperature inversions, which produce a temperature gradient that favors the transmission of sound, are quite common during the evening hours. Louder sounds may be audible for several miles under certain conditions, when background levels are low and their masking effect is negligible; airport noise is particularly susceptable to this phenomenon. No amount of screening short of full enclosure appears to be effective

against long distance noise propagation due to temperature inversions.

With all factors considered it appears that a 20 dB reduction (about one fourth as loud) is about the practical maximum obtainable, and any further reduction must be made by attacking the noise at its source.

In spite of the difficulty of outdoor noise control, the requirements are often less stringent than might be first imagined. Surveys along major highways have shown sound levels below 68 dBA to be acceptable for out-of-door daytime activities, although noise control experts seem to favor 65 dBA as a desirable maximum. Evening levels are somewhat lower, and levels below 50 dBA are desirable for quiet neighborhoods. Camping requirements, which might seem severe, are somewhat modified by the masking effect of natural sounds - the rustle of leaves, the songs of birds, and the breaking of twigs underfoot. None of these requirements compare with those of the library, theater or recording studio, where background levels in the 15 to 30 decibel range are mandatory.

Many of our common noises can be brought below the disturbing level by the means suggested, because a 10 dB reduction is often sufficient to do this, and is not too difficult to obtain.

RECOMMENDATIONS

The following recommendations are based on the results of this study of combinations of trees and land-forms for noise control. Additional recommendations based on the preceding study, where plant materials were used exclusively, are found in the report of the initial study (11).

1. To reduce noise from high-speed car and truck traffic, construct a land-form of sufficient height to screen the traffic from view, and plant several rows of trees and shrubs adjacent to and on the land-form for progressive improvement. Conifers are preferred to deciduous varieties where year-round protection is desired.
2. To reduce noise from moderate-speed auto traffic in suburban areas, plant rows of heavy shrubs adjacent to the traffic lanes, and construct a low (5 to 6 foot) land-form or similar solid barrier immediately behind the shrubs. Also plant taller varieties of trees adjacent and parallel to the barrier to extend the effective distance.
3. Although optimum land-form height will vary for each situation, 8 to 10 foot heights, when used in combination with taller varieties of trees, are recommended for general application. The noise source must be screened from view, however.
4. The noise screen should be placed relatively close to the noise source to achieve maximum benefit. However, the area immediately behind a screen relatively far from a noise source also receives considerable protection. The screen must extend

far enough from side to side to assure acceptable sound levels at the protected area.

5. Wind speed and direction affect sound level at a specific location. Therefore the most severe condition (high wind in the direction of sound propagation) should be used when estimating expected sound levels for design purposes.
6. Natural ground configurations, such as hills, ridges, and depressed highways, should be employed to serve as noise screens when planning roadside developments along highways, and when locating parks, playgrounds, schools, and residences adjacent to arterial streets in urban areas.
7. Existing trees, shrubs, and grass should be left undisturbed, as far as possible, rather than replacing the soft materials with harder reflecting surfaces detrimental to noise control.

FUTURE STUDY

1. Studies to determine the most effective placement, size, and combinations of hedges, trees, walls, and other solid barriers would bring the use of plant materials for noise control to bear on the problem of suburban noise, which some highway design experts feel is the greatest noise control problem they face today.
2. Long-term studies, using plantings specifically designed for noise control, are needed to separate the effects of such factors as tree type and height, belt width, belt density, wind (speed, direction, and gradient) and temperature gradients to provide more accurate design criteria.

3. Studies using models of trees, shrubs, and other devices for noise control could lead to predictions of noise levels and attenuations. A mathematical model would remove the time requirement and construction expense of a full-size facility, and could lead to a relatively precise and inexpensive method for computer-aided design of noise control screens.

APPENDIX A

GLOSSARY OF TECHNICAL TERMS

Attenuation - A reduction in value, often applied to measurements of sound and electricity.

Decibel (abbreviated dB) - A logrithmic ratio used in sound and electric power measurements, wherein the denominator is a reference quantity. (see Sound Pressure Level)

dBA - A "weighted" measure of sound pressure level which provides relatively high correlation with subjective estimates of loudness of certain noises. (see Sound Level)

Free Sound Field - A field in a uniform medium surrounding a sound source, which is relatively free from boundry effects (echo etc.).

Frequency - The time rate of repetition of a periodic phenomenon, having units of cycles per second (Hz). In sound control measurements variations of air pressure from 20 Hz, to 15,000 Hz adequately represent the audible range.

Level - A physical measurement of a quantity referred to a similar reference quantity (usually lower in value). In accoustics, sound power level and sound pressure level are the usual levels encountered.

Loudness - The intensive attribute of an auditory sensation; a subjective quantity, dependent on frequency and pressure, and ranging from soft to loud. (see Sone and Phon)

Loudness Level - The loudness level of a sound, in phons, is numerically equal to the sound pressure level, in decibels, of a 1000 Hz tone judged equally loud.

Microbar - A unit of pressure equal to 1 millionth of the standard atmospheric pressure, also equal to one dyne per square centimeter.

Noise - Any unwanted sound, usually an erratic random oscillation, also applied to electric waves.

Noise Level - A degredation of sound level, used where disagreeable sound (noise) is being considered.

Octave - An interval between two pure tones or oscillations having a frequency ratio of two.

Octave Band - Segment of the audio spectrum having a width of one octave. For convenience of analysis ten standard octave bands having geometric mean frequencies of 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, 16000 Hz are often used.

Phon - The unit of loudness level (see Loudness Level)

Sone - The unit of loudness - One sone corresponds to a 1000 Hz tone of 40 dB intensity. Any sound that is judged to be n times that of this one-sone tone is n sones. Sones are related to Phons through the expression

$$S = 2^{\left(\frac{P-40}{10}\right)}$$

Sound - An oscillation in pressure, particle displacement, velocity etc., in an elastic medium, capable of affecting the hearing mechanism, in the ordinary sense.

Sound Level - A weighted sound pressure level obtained by tailoring the response characterists of Sound Level Meters to meet certain criteria, for example: dBA is the A-scale weighted sound pressure level and dBC is the C-scale weighted sound pressure level (essentially flat or uncorrected in the audio range). Scale characterists are specified by the American Standards Association.

Sound Pressure Level (SPL) - A measure of the rms sound pressure relative to an arbitrary reference pressure approximating the threshold of hearing. Definition by equation is

$$\underset{\text{(decibels)}}{SPL} = 20 \log (P/P_o)$$

where P_o = reference sound pressure of .0002 dynes per sq cm (microbars)

P = measured sound pressure

Speech Interference Level (SIL) - The average, in decibels, of the sound pressure levels in the octave bands which contain most of the speech frequencies i.e. the 500, 1000, and 2000 Hz unit frequency bands.

Concepts Relating the Decibel to the Physical Senses

The audible range of sound pressures extends from approximately zero decibels at the threshold of audibility to approximately 130 decibels at the threshold of feeling or pain.

The majority of ordinary sounds we hear fall in the range of about 25 decibels (a quiet library) to about 80 decibels (a very noisy street corner).

A difference of one decibel is the smallest change in loudness which can be easily detected by the ear.

An increase of ten decibels corresponds to approximately doubling the apparent loudness of a sound for most of the audible range.

APPENDIX B

AN ABBREVIATED LIST OF PLANT MATERIALS SUITED FOR USE IN NOISE ABATEMENT

Arborvitae, American (northern white cedar)[a]	Thuja occidentalis L.
Arborvitae, oriental[a]	Thuja orientalis L.
Cedar, atlas	Cedrus atlantica Manetti
Cedar, deodar	Cedrus deodara (Roxburgh) Loudon
Cedar, of Lebanon	Cedrus libani Loudon
Cedar, Japanese	Cryptomeria japonica (Linneaus fil.) Don.
Cedar, Port-Orford	Chamaecyparis lawsoniana (A. Murr.) Parl.
Cotoneaster	Cotoneaster sp. B. Ehrh.
Cypress, Arizona	Cupressus arizonica Greene
Douglas-fir	Pseudotsuga menziesii (Mirb.) Franco
Euonymus	Euonymus sp. L.
Fir, balsam	Abies balsamea (L.) Mill.
Fir, California red	Abies magnifica A. Murr.
Fir, corkbark	Abies lasiocarpa var. arizonica (Merriam) Lemm.
Fir, Fraser	Abies fraseri (Pursh) Poir.
Fir, Nikko	Abies homolepsis Siebold & Zuccarini
Fir, Spanish	Abies pinsapo Boissier
Fir, Veitch's silver	Abies veitchii Lindley
Fir, white	Abies concolor (Gord. & Glend.) Lindl.
Hemlock, Carolina	Tsuga caroliniana Engelm.
Hemlock, eastern	Tsuga canadensis (L.) Carr.
Hemlock, western	Tsuga heterophylla (Raf.) Sarg.
Honey locust	Gleditsia triacanthos L.
Juniper, Chinese[a]	Juniperus chinensis L.
Juniper, eastern (redcedar)[a]	Juniperus virginiana L.
Juniper, Grecian	Juniperus excelsa Bieberstein
Juniper, Irish	Juniperus communis var. hibernica (Loddiges) Gordon
Juniper, Rocky Mountain	Juniperus scopulorum Sarg.
Juniper, Swedish	Juniperus communis var. suecica Aiton.
Lilac	Syringa vulgaris L.

Mulberry	Morus alba var. tatarica Loud.
Pine, Austrian	Pinus nigra Arnold
Pine, eastern white	Pinus strobus L.
Pine, Monterey	Pinus radiata D. Don
Pine, mugo (Swiss mountain)	Pinus mugo Turra
Pine, ponderosa	Pinus ponderosa Laws.
Pine, red	Pinus resinosa Ait.
Pine, Scotch	Pinus sylvestris L.
Pine, western white	Pinus monticola Dougl.
Privet	Ligustrum sp. L.
Pyracantha (Firethorn)	Pyracantha coccinea Roem.
Redcedar, western	Thuja plicata Donn.
Redwood	Sequoia sempervirens (D. Don) Endl.
Sequoia, giant	Sequoiadendron giganteum (Lindl.) Buchholz
Spruce, blue (Colorado)	Picea pungens Engelm.
Spruce, Norway	Picea abies (L.) Karst.
Spruce, Oriental	Picea orientalis (L.) Carriere
Spruce, Serbian	Picea omorika (Panocie) Bolle.
Spruce, white	Picea glauca (Moench) Voss
Yew, English[a]	Taxus baccata L.
Yew, Japanese[a]	Taxus cuspidata Siebold & Zuccarini

[a] The type and horticultural varieties and cultivars.

APPENDIX C

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